Geological recognition of abrupt marine invasions in two coastal areas of Portugal

A thesis submitted for the degree of Master of Philosophy

by

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August 2006

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Declaration

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Abstract

Abrupt marine invasions such as tsunamis and storms are particularly devastating for coastal areas. They may also leave a permanent record in the sedimentary deposits which is the principal focus of this thesis. In historical times the most destructive tsunami that affected Europe was the AD 1755 Lisbon. The effects and consequences of the AD 1755 tsunami are presented. The causes, propagation and behaviour of tsunamis are also discussed.

Sedimentological criteria to identify abrupt marine invasions in the stratigraphic column are presented from literature.

This thesis aims to contribute to a better understanding of the signature left by abrupt marine invasions in coastal stratigraphy by investigating the nature of the sedimentary record associated with tsunamis in a region of their known impact. A wide range of proxies was used to detected tsunami and storm deposits in 2 coastal areas of Portugal. The techniques used include stratigraphic description, grain size analysis, digital and x-ray photography, magnetic susceptibility, macrofossils analysis, geochemical analysis and ^{210}Pb and Optically Stimulated Luminescence dating.

The investigated areas (e.g. Lagoa de Óbidos (Central Portugal) and Martinhal (South Portugal)) were affected by the AD 1755 tsunami. The locations have similar geomorphological features and are both susceptible to major abrupt marine invasions. Results show that an abrupt event deposited unique sedimentary units in both locations. A similar age for the event was established. A considerable number of tsunami sedimentary characteristics were detected in both units.

However, a key outcome of this research is the demonstration of the difficulty of distinguishing between sedimentary deposits laid down by tsunamis, and those deposits resulting from storm action; consequently the geological record of tsunamis almost certainly underestimates their frequency.

Acknowledgements

To achieve the degree of MPhil I received the help and support of many people.

First of all I would like to thank my first supervisor Professor Suzanne Leroy, not only for the patience to deal with my queries, but also for the enthusiasm and the immense support to this project. She made me persist until the thesis was complete. The fieldwork and laboratory experience I had while working with her was crucial for my MPhil. My other supervisor, Dr Stephen Kershaw was always cooperative and available to discuss, read or comment the data or chapters I was producing. He encouraged me many times and his words were very important to carry on working on this thesis. I also wish to thank Dr Jorge Dinis for his support and, especially, for his involvement and commitment during the coring campaigns.

In addition, I would like to thank my examiners, Professor Alastair Dawson and Dr Phil Collins, for the constructive discussion during my exam.

I would also like to express my appreciation to Dr Stella Kortekaas for the constructive discussions we had and for the permission to access cores collected in Martinhal.

I wish to thank Dr Iain Stewart, Dr Susana Vilanova and Dr César Andrade for the useful suggestions and comments. Moreover I would like to express my gratitude to Dr Phillip Toms for his assistance during the OSL dating and the granulometry analysis and to Mr Paul Szadorski for all the help with the logistics and the geochemical analysis. I also wish to express my thanks to Ms Sue Buckingham, Dr Leo Zelig, Dr Thomas Dewez and to other staff members at the Department of Geography and Earth Sciences.

I am thankful to many of my friends for their help in many occasions during this period, especially to Rui Henriques and Carla Nascimento.

Especially I would like to express my immense gratitude to my parents, my brother and my uncle for all the encouragement and support.

Finally I would like to express my enormous appreciation to my grandfather and to Paula.

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1. Introduction

1.1- Background

The study and interpretation of the evolution of a given coastal area requires independent and precise historical documentation, knowledge of the characteristics of the shoreline and, more significantly, the accurate analysis of the depositional record. Extreme events, such as abrupt marine invasions (e.g. tsunami, storm surges and coseismic subsidence), have an undoubtedly important significance to coastal evolution. Abrupt marine invasions are events of low frequency but with high magnitude that often leave a characteristic geological signature.

Over the past 20 years an increasing number of papers have been published concerning the interpretation of the lithological signature of abrupt marine invasions (see page 27 and 28). The majority of references found concern studies on palaeotsunamis. However, the impacts of storm deposits should also be considered in the study of coastal stratigraphy. Furthermore, only recently (last decade) approximately ten different studies focused on the stratigraphic signature of modern tsunamis but even less papers have been published concerning the sedimentary differentiation between different abrupt marine invasions. However, differentiating the geological signature of each type of abrupt marine invasion is crucial to access the hazard risk of coastal areas and establish patterns of coastal flooding.

Due to specific depositional conditions, the stratigraphy of coastal lagoons is the best geological setting to detect units deposited by abrupt marine invasions because the low energy of lagoons is a suitable place to detect sudden energy increase from their sedimentary record.

A better understanding of the phenomena of abrupt marine invasions is required to increase the knowledge, not only of the origin and propagation of the event but also of its geological consequences. The geological signature deposited by abrupt marine invasions in coastal areas is the subject of this research.

The Portuguese coast, although not frequently subjected to tsunamis, was strongly affected by the AD 1775 Lisbon Tsunami. Previous studies confirmed the existence of a sedimentological signature of this tsunami in the South coast of Portugal (e.g. Algarve) (Andrade, 1992; Dawson et al., 1995; Hindson et al., 1996; Kortekaas, 2002) but the tsunami deposit was also detected in the stratigraphy of Cadiz, in Spain (Dabrio et al., 1998; Luque et al., 2001) and in the Scilly Isles, in the United Kingdom (Foster et al., 1993).

The study areas were selected based on historical references and on geomorphological features. According with historical descriptions the locations selected (e.g. Lagoa de Óbidos and Martinhal) were affected by the 1755 earthquake. Lagoa de Óbidos, 80 kilometres north of Lisbon in Central Portugal, is a coastal lagoon separated from the sea by a sand barrier; while Martinhal, near Sagres in the Algarve, is a small flat estuarine valley. Moreover, in Martinhal the AD 1755 tsunami has been already detected by Kortekaas (2002).

1.2- Research objectives

From the background given above, a number of aims were identified that determined the process of this research:

1) To identify, compare and differentiate sedimentary units deposited by abrupt marine invasions (e.g. tsunamis and storms) in two locations of the Portuguese coast. The specific target of this thesis is the recognition of sediments deposited by the well known AD 1755 Lisbon Tsunami.

2) To evaluate which proxy (e.g. stratigraphic, granulometric, palaeontological or geochemical) or proxies, if any, is/are more useful in recognising abrupt marine invasions.

3) To compare the geological features of tsunami and storm surges, if present in the same location.

4) To assess the limitations of the differentiation of abrupt marine invasions studied.

1.3- Thesis structure

The thesis is divided into 4 parts (Figure 1.1):

a) Literature Review (Chapter 2, 3 and 4)
b) Methodology (Chapter 5)
c) Results (Chapter 6 and 7)
d) Discussion and Conclusions (Chapter 8 and 9)

After a brief introduction to the theme, to the global aims of this research and to the structure of the thesis (Chapter 1), the thesis continues with an extensive Literature review (Chapters 2, 3 and 4). In the literature review a considerable number of papers referring to the physics of tsunamis, the geological evidence of tsunamis and storms and the effects of the AD 1755 are mentioned.

In Chapter 2- Physics of tsunamis: a concise review- a significant review of the mechanisms that control the generation, propagation and behaviour of tsunamis is presented.

Chapter 3- Geological evidence of tsunami and storms- presents a comprehensive review of the main geological features that characterise a tsunami and storm deposit. The limitations of the differentiation of tsunami and storm deposits are also discussed in Chapter 3. Moreover, a review of papers published concerning the AD 1755 tsunami sedimentary signature is also presented.

Chapter 4- The AD 1755 Tsunami- is focused on the impacts of the AD 1755 tsunami. Based on historical documents the catastrophic effects of the tsunami are mentioned.

In Chapter 5- Methodology- a detailed description of all proxies and techniques used during this research is presented. In this chapter exhaustive explanation of the following procedures can be found: historical record, coring, stratigraphic description, x-ray and digital photography, magnetic susceptibility, geochemical analysis, grain size analysis, palaeontology and dating methods.

Chapter 6 (Lagoa de Óbidos) and Chapter 7 (Martinhal) present the final results of each location. The chapters start with a brief analyse of previous studies and the geological setting of the study areas. The presentation of results from every proxy follows the order of Chapter 5- Methodology. At the end of both chapters results of the respective location are discussed.

In Chapter 8- Discussion- the results from the two study areas (Lagoa de Óbidos and Martinhal) are discussed.

Chapter 9 presents final conclusions of this research. This chapter starts with a summary of the results, followed by discussion of the evidence of tsunami deposits and the limitations of differentiation between tsunami and storm deposits. Future work is proposed at the end of the chapter.

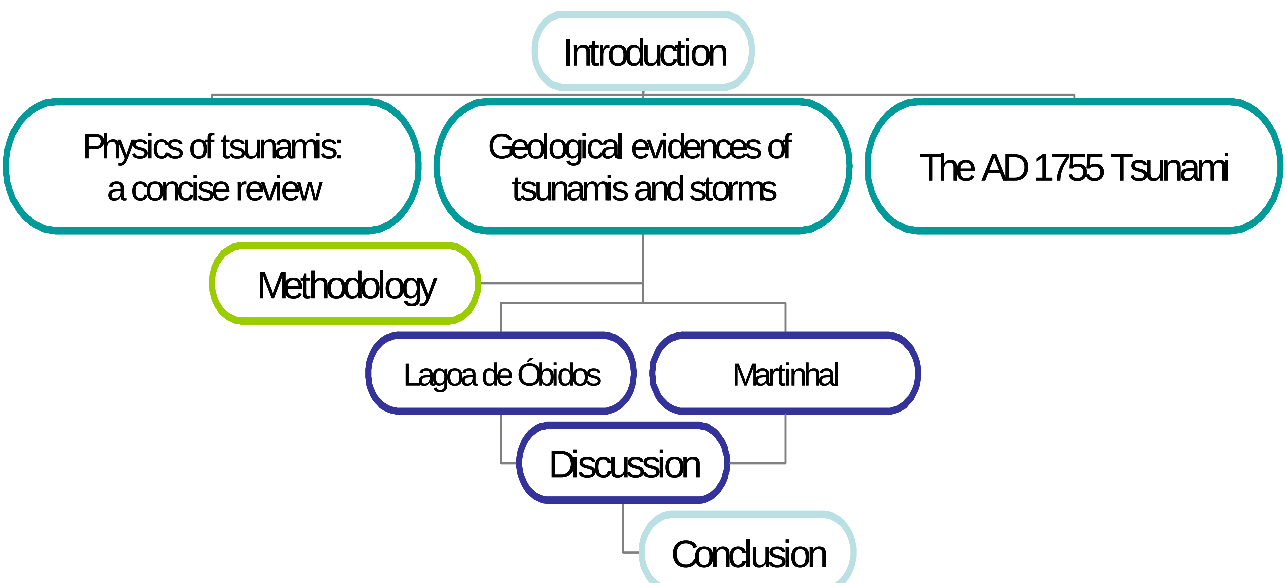

Figure 1.1- Thesis structure

2. Physics of tsunamis: a concise review

2.1- Introduction – Definition and principal characters of tsunamis

Tsunami is the Japanese word that describes a "harbour wave". According to Lapidus (1990), "Tsunami is the gravity-wave system that follows any short-duration, large-scale disturbance of the free sea surface."

Their causes are related with geological processes such as earthquakes, landslides, volcanic eruptions and meteoritic, asteroids and comets impacts.

A tsunami travels outward from the source region as a series of waves. Wave velocities reach speeds of 900 km/h over deep ocean. Tsunamis are usually small and barely noticed in deep oceans, but the waves become large and cause damage when they approach coastal areas. "As waves approach the coastline, the speed of the waves decreases as they are deformed within shallower water depths" (Lapidus, 1990). Tsunamis can travel virtually unnoticed through the open ocean because the wave height may be very small but as soon as they reach nearby-shore the wave height increases. Destruction from tsunamis is the direct result of inundation, wave impact on structures and erosion.

The scientific community is devoting extreme care and attention to all kinds of natural hazards that can disturb the welfare of humankind. Tsunamis, despite being rare catastrophic events, are regarded as a major threat. Extensive study of tsunami hazards is currently going on in many parts of the world, although tsunamis occur mainly in the Pacific. The catastrophic tsunami event in the Indian Ocean in 2004 was important in terms of the impact that had in the public opinion.

Tsunami research has developed astonishingly in the last 40 years, and has become a multidisciplinary subject involving sedimentologists, historians, geomorphologists, seismologists, palaeoecologists and geochronologists.

Several investigations have been conducted globally with the purpose of determining controls and eventually, mitigating the destructive effects of tsunamis.

Tsunamis are long water waves set in motion by an impulsive perturbation of the sea acting over a very large area. The processes and mechanisms that generate tsunamis are discussed. Tsunamis are analogous to wind waves and behave like them. Tsunami behaviour and propagation is discussed in this chapter. Tsunamis have a wave length, a period, a deep-water height and can undergo shoaling, refraction and diffraction. Instrumental registrations of tsunami are most frequently observed on the records of mareograph stations. Tsunami classifications are discussed.

Tsunamis usually leave a strong sedimentological signature. The study of palaeotsunamis is based primarily on the collection and analysis of tsunami deposits found in coastal areas. The research over palaeotsunamis can provide a significant amount of information about past tsunamis to aid in the assessment of the tsunami hazard.

In conclusion, tsunamis are major natural disasters that can cause destruction in coastal areas and loss of human live. To understand the mechanisms of generation and propagation of tsunamis is undoubtedly important to prevent the effects of tsunamis in coastal areas.

2.2- The Behaviour of tsunamis

A tsunami can be divided into three phases, the generation (discussed in the following pages), the propagation to the coast and the run-up at the shoreline.

“Once the tsunami is formed, the wave system closely resembles that which is produced by throwing a stone into a pond.” (Lapidus, 1990). “The wave configuration is axi-symetric and consists of concentric rings of crests and troughs. The front expands at the velocity of $c = \sqrt{gh}$ in which g is gravitational acceleration and h is the water depth. Within several minutes after the generation process, the initial tsunami is split into a tsunami that travels out to the deep ocean (distant tsunami) and another tsunami that travels towards the nearby coast (local tsunami)” (Lapidus, 1990). Several events happen as the local tsunami travels over the continental slope. The most obvious one is that the amplitude increases. The tsunami's energy flux, which is dependent on both its wave speed and wave height, remains nearly constant. Consequently, as the tsunami's speed diminishes as it travels into shallower water, its height grows. Because of this shoaling effect, a tsunami, imperceptible at sea, may grow to be several meters in height near the coast.

Physical laws can explain the wave propagation. “If the tsunami wavelength is much smaller than the scale of velocity heterogeneity, i.e., the depth change, then we can apply the geometrical ray theory of optics.” (Satake, 1999). Moreover, “their propagation path is sensitive to the ocean bathymetry that, analogously to an optical lens, may focus or defocus the tsunami rays, thereby increasing or decreasing the wave amplitude” (Tinti, 1990).

As the tsunami wave travels from the deep-water, continental slope region to the near-shore region, tsunami run-up occurs. Run-up is a measurement of the height of the water onshore observed above a reference sea level.

After run-up, part of the tsunami energy is reflected back to the open ocean. In addition, a tsunami can generate a particular type of wave called edge waves that travel back and forth, parallel to shore. These effects result in successive arrivals of waves at a particular point on the coast rather than a single wave. Because of the complicated behaviour of tsunami near the coast, the first run-up of a tsunami is often not the largest (emphasising the importance of not returning to a beach several hours after a tsunami hits).

A strange behaviour occurs in the sea close to shore areas. “Different sets of conditions apply in shallow water near the shore, and when a tsunami is inundating the coast. There are several terms that are used to describe this phenomenon. The one to use depends on circumstances (e.g., whether the tsunami is in a bay) and on personal preference. The term’s “negative wave”, “drawdown” and “withdrawal” are most often used to describe this type of initial onset. Less formal are the terms 'waterline receding' and “bay emptying”. The underlying reason for this effect is that both offshore landslides and subduction zone earthquakes create a negative wave on the shoreward side of the bottom deformation. This negative wave propagates to shore and produces the drawdown." (GITEC-2, 1995).

In coastal areas the devastation can be enormous. The destruction in infrastructures caused by tsunamis is due to "drag and flotation forces associated with the waves , strong induced currents and floating debris" (Tinti, 1990). The tsunamis tend to decrease with distance from the source point.

2.3- Causes of Tsunamis

A tsunami can be generated by any disturbance that displaces a large water mass from its equilibrium position. Geological processes such as earthquakes, landslides, volcanic eruptions and meteoritic impacts can cause tsunamis (Figure 2.1).

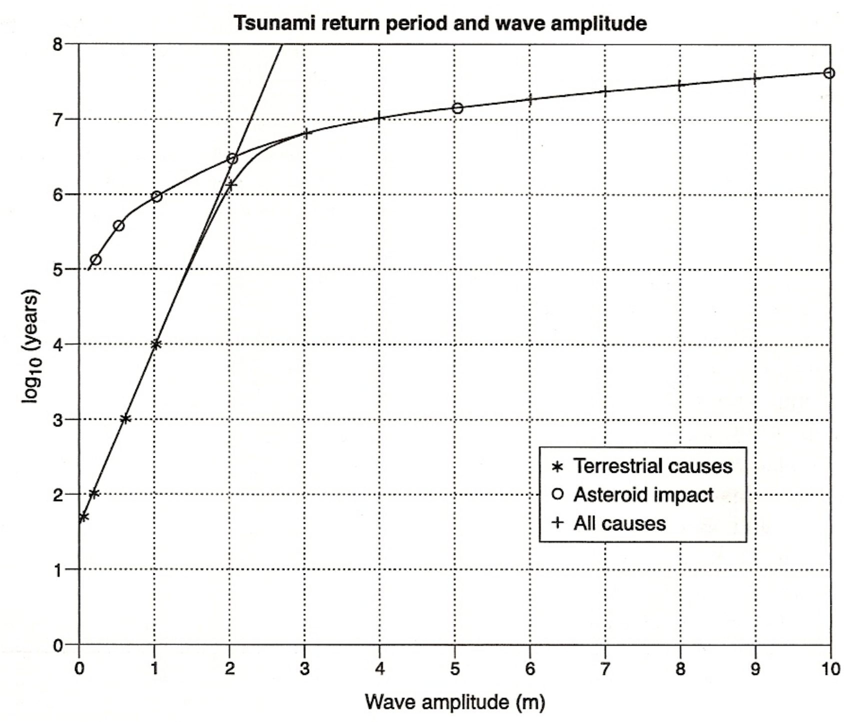

Figure 2.1- Schematic illustration of calculating tsunami risk based on the combination of low return frequency events (e.g. asteroid impact) and other types of tsunami risk (e.g. offshore earthquake, submarine slide) characterised by higher return frequencies. (Dawson et al, 2004)

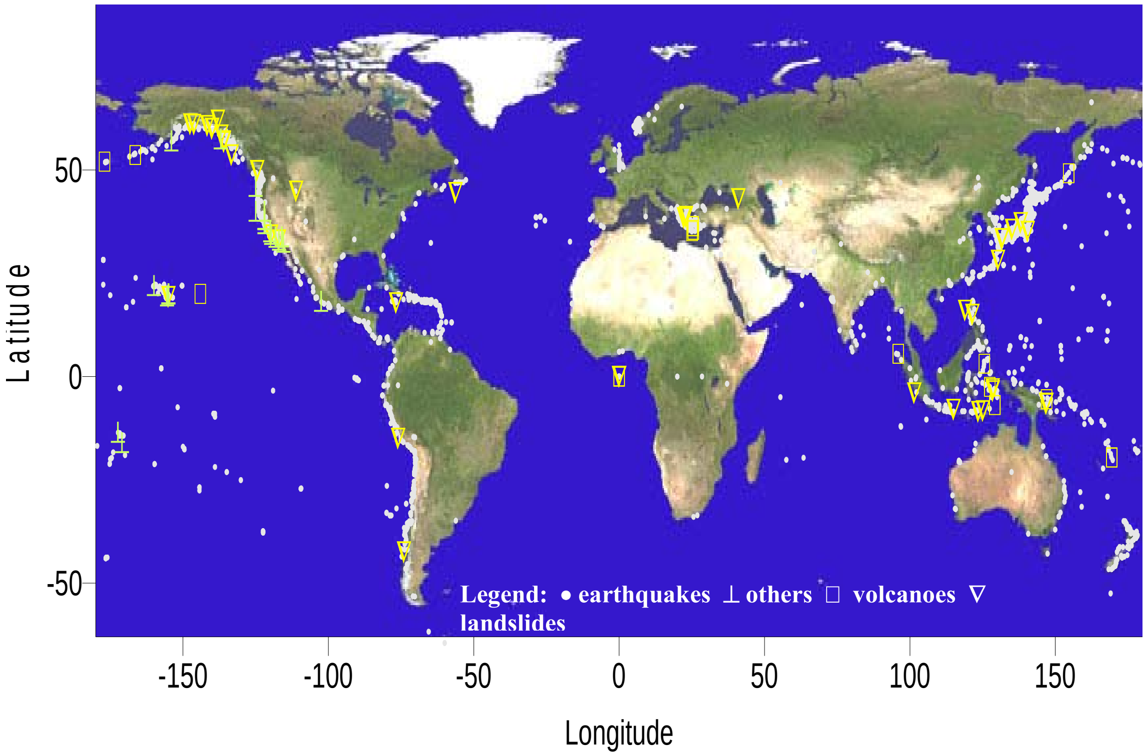

Figure 2.2: Sources of tsunamis in the last 3500 years (adapted from NGDC database, 2001)

Historically tsunamis have been a constant threat to humans. In the following map (Figure 2.2), based on historical and instrumental data from the National Geophysical Data Center (NGDC), the causes and location of tsunamis in the last 3500 years in the World is presented.

2.3.1- Earthquakes

Earthquakes are the main source of tsunamis. When earthquakes occur beneath the sea, the water above is displaced from its equilibrium position. Waves are formed as the displaced water mass, which acts under the influence of gravity, attempts to regain its equilibrium. When large areas of the sea floor elevate or subside, a tsunami can be created. Large vertical movements of the earth's crust can occur at any faulted plate boundaries, but “earthquakes on the continental side of the subduction trench are particularly effective generating tsunamis” (Furumoto & Fukao,1985).

For distant tsunamis that have travelled far from the origin of the earthquake, the magnitude of the earthquake is a good measure of the size of the tsunami. For local tsunamis, however, more knowledge than the magnitude is needed to calculate the final run-up of the tsunami. Earthquake sensitive areas in the world and tsunamigenic areas are related.

2.3.2- Landslides

Two major types of landslides that can create tsunamis can be considered, underwater and coastal landslides. Several mechanisms can trigger these landslides: small earthquakes, collapse of volcanoes or their flanks and erosion in submarine slopes. One example of an underwater slide that caused a trans-Atlantic tsunami was the Storegga slide circa 7200 ^{14}C years ago. This event is one of the most studied tsunamic events in the World. Furthermore, it is important to recognise that in non-seismic areas, submarine slides are the main tsunamigenic sources.

In the coastal areas slopes are subject to several erosion forces such as rainfall, storms and especially sea waves. Furthermore, "The slumps generally follow greater-than-usual storms, which remove substantial amounts of material and lead to a sudden decrease in the stability of the slope" (Bolt et al., 1975). This leads to considerable quantity of rocks, sand and debris to fall over the ocean causing a perturbation of the sea surface and eventually causing a tsunami.

2.3.3- Volcanoes

Volcanic eruptions above sea level, due to the collapse of the volcanic crater or the collapse of one of its flanks, can generate rock falls, debris flow and rockslides that reach the sea causing a tsunami. This is only been discussed, so far, in the context of volcanic islands. But the major volcanic generating tsunami sources are the underwater eruptions, not only the displacement of materials in the slope of the volcano but also the release of gas can provoke a tsunami. The eruption itself can cause a small earthquake that can trigger a tsunami. "Volcanoes with Plinian activity characterised by huge destructive explosions and consequent collapse of the caldera may give origin to giant waves" (Tinti, 1990).

Historically, there are many examples of volcanic tsunamis; however the Santorini eruption, not only for its social and cultural importance, but also for its geographical proximity with the Iberian Peninsula, deserves special reference. "The collapse of the caldera of the volcano Santorini during a major eruption 3500 years BP caused a huge tsunami which inundated surrounding islands and is recorded in the lore of many circum-Mediterranean cultures" (Kastens & Cita, 1981).

2.3.4- Meteors

The Earth is subject to bombardment from space. Asteroids, comets and meteorites, can cause catastrophic events if they collide with the Earth. If a major meteorite collides with the Earth in an urban area, the devastation would be enormous, but the biggest devastation would be caused if it falls over the ocean.

"Tsunami is probably the most serious form of damage caused by stony asteroids with diameters between about 200 m and 2 km." (Hills & Goda, 1998). In Figure 2.3 a compilation of the estimated wave height (above sea level) at different distances from the impact zone from different authors is presented.

A group of studies has been conducted trying to predict the consequences of a tsunami caused by an asteroid or by a meteorite. "We find that an asteroid 5 km in diameter falling in the mid-Atlantic produces tsunamis that inundate the upper two thirds of the Eastern United States. "..." In Europe, the damage is less dramatic. The most vulnerable areas are Portugal and Spain. It is being thrust into the Atlantic by plate tectonics, so it has little continental shelf, which is ideal for producing large tsunami run-ups. "..." The situation in Northern Europe is more favourable." (Hills & Goda, 1998). However, the probability of such event in a human lifetime is close to zero. "For these highly vulnerable coastal areas the typical interval between asteroid tsunami events is likely to be about 200,000 years - assuming that impacts are randomly distributed in time.” (E. A. Bryant, pers. comm., 2002).

It is possible that tsunamis caused by asteroids produce much higher waves than others tsunamis caused by “more frequent” geological phenomena. For example Mader (1988) calculated wave heights from the Eltanin impact site (coast of Chile) would have been 130m at Hawaii, 40m at the California coast and 60 m off Japan.

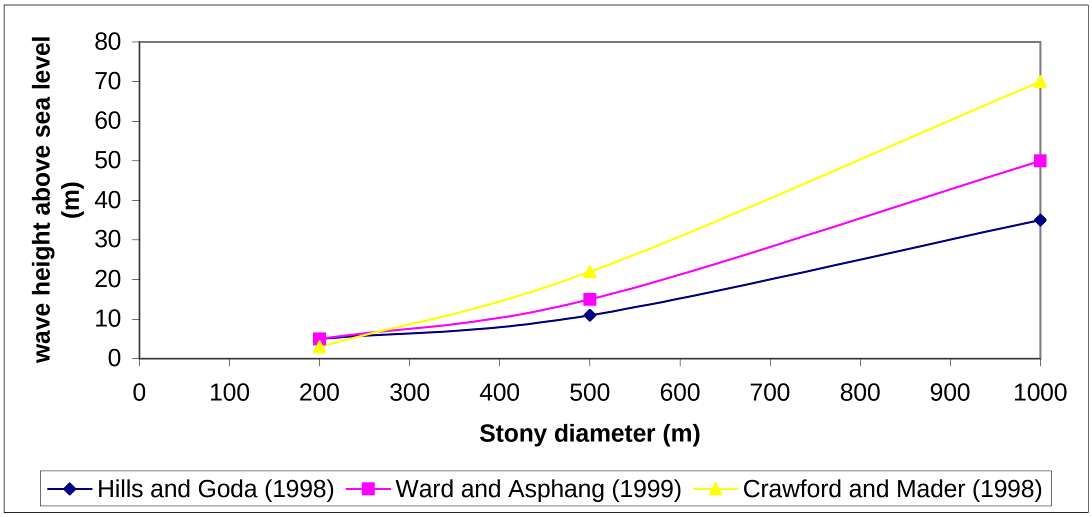

Fig. 2.3: Estimated deep water height at a point 1000 km from asteroid impact.

2.4- Tsunami classification

The two most important aspects that characterise tsunamis are the magnitude and the intensity. Briefly the most important scales are presented.

2.4.1- Tsunami magnitude scale

In terms of magnitude scales, tsunamis can be divided as follows.

The traditional magnitude scale is the so-called Imamura-Iida (m). The value is approximately equal to $m=\log_2 h$, where *h* is the maximum run-up height in m. This scale is similar to the earthquake intensity scale, and is especially convenient for old tsunamis from which no instrumental records exist. Hataori (1979) extended the Imamura-Iida m scale to include far-field tsunami data. He also considered the effect of distance. Another magnitude scale, M_t, called tsunami magnitude, is defined and assigned for many earthquakes by Abe. The definition of M_t for a Trans-Pacific tsunami is (Abe, 1979): $M_t = \log H + C + 9.1$ And for a regional tsunami (100km< Δ< 3500km) tsunami is (Abe, 1981): $M_t = \log H + \log \Delta + 5.8$ Where H is the maximum amplitude on tide gauges in meters, C is a distance factor depending on a combination of the source and the observation points and Δ is the actual distance in km. The above formulas where calibrated with the moment magnitude 3 scale, M_w, of earthquakes. However, in tsunamis triggered by submarine slides the magnitude scale cannot be applied.

2.4.2- Tsunami intensity scale

For tsunami intensity there are two different scales.

Soloviev (1970) pointed out that Imamura-Iida's scale is more like an earthquake intensity scale rather than a magnitude. He also distinguished the maximum tsunami height h and the mean tsunami height $\underline{h}$. He then defined tsunami intensity i as

$$i = \log_2(\sqrt{2}\,\underline{h}).$$

Sieberg tsunami intensity scale – a descriptive tsunami intensity scale which was later modified into the Sieberg-Ambraseys tsunami intensity scale (Ambraseys, 1962)- describes tsunamis from light tsunamis (Level 1) to disastrous tsunamis (level 6) based on the physical destruction caused by tsunamis (Table 2.1).

Level	Consequences
Level 1 – Very light	Wave so weak as to be perceptible only on tide-gauge records.
Level 2 – Light	Wave noticed by those living along the shore and familiar with the sea. On very flat shores generally noticed.
Level 3 – Rather strong	Generally noticed. Flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coasts. In estuaries reversal of the river flow some distance upstream.
Level 4 – Strong	Flooding of the shore to some depth. Light scouring on man-made ground. Embankments and dikes damaged. Light structures near the coasts damaged. Solid structures on the coast injured. Bid sailing vessels and small ships drifted inland or carried out to sea. Coasts littered with floating debris.
Level 5 – Very strong	General flooding of the shore to some depth. Quay-walls and solid structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land and littering of the coast with floating items and sea animals. With the exception of big ships all other vessels carried inland or out to the sea. Big bores in estuaries. Harbour works damaged. People drowned. Wave accompanied by strong roar.
Level 6 – Disastrous	Partial or complete destruction of man-made structures for some distance from shore. Flooding of coasts to great depths. Big ships severely damaged. Trees uprooted or broken. Many casualties.

Table 2.1- Sieberg-Ambraseys tsunami intensity scale (Ambraseys, 1962)

2.5- Models, predictions and mitigation

The tsunami risk of Iberian Peninsula can be considered as low to moderate, based on statistical and historical analysis of the occurrences of earthquakes and tsunamis. Predicting an event such as a tsunami is complicated. Simões et al. (1992) proposed a recurrence time schedule for the Iberian Peninsula (Table 2.2).

Tsunami description	Earthquake Magnitude	Recurrence time (yrs)
Normal	7.5	200
Destructive	8.0	450
Very destructive	8.5	1000
Exceptional	9.0	2500

Table 2.2 - Recurrence time for tsunamis in the Iberian Atlantic coasts (Adapted from Simões et al., 1992)

Irrespective of the cause, there is the need to assess the risk to coastlines from tsunamis. Moreover, several tsunami run-up models have been developed all over the World. In the Iberian Peninsula models based on historical and instrumental data have produced probable scenarios of the consequences of future tsunamis. Ward & Day (2001) presented a model for a tsunami caused by a lateral collapse of the Cumbre Vieja, in the Canary Islands. This model presented alarming results for La Manga Tsunami. The waves created by the landslide would destroy areas in the African coast (one hour after the collapse) and Eastern American coast (nine hours after the collapse), but also would devastated the Atlantic Iberian coast (two hours after the collapse) and the SW Britain (four hours after the collapse).

Not only predicting the consequences of future tsunamis (e.g Ward & Day, 2001) but also calculating the real devastation of past tsunamis (e.g. AD 1755- Baptista et al., 1998b; Heinrich et al., 1994) are possible today using geophysical and mathematics models. This permits to have clear ideas of susceptible areas and will allow the development of tsunami hazard assessments that would decrease the future impact of tsunamis.

To develop more effective warning system in the areas most susceptible of being affected by tsunamis in the Peninsula is important. The lapse of time between the origin and the arrival of a tsunami is short, making impossible to organise large-scale retreats of people or goods. But, it would allow a better answer from the emergency services in case of a devastating tsunami. Examples like the Tsunami Warning System in Japan, Hawaii, California or Oregon should be followed, although in a smaller scale.

Moreover, in the Iberian Peninsula a warning system develop by the University of Lisbon and the CPRM Marconi, in the frame of the project called Destructive Earthquakes and Tsunami Warning System (DETWS), has been active since 1992. "This warning system consists of ocean buoys, which contain electronic subsystems linked below by cable to the ocean floor and above, via satellite (INMARSAT-C), to the processing centre." (GITEC-2-EU funded, 1995). The Iberian Peninsula is also being monitored by TREMORS (Tsunami Risk Evaluation through seismic Moment from real-time system). This system is composed "of a three-component broad band seismometer associated with a PC and its dedicated software. It is able to identify tsunamic earthquakes by using the evaluation of the seismic moment extracted from the mantle magnitude M_m after automatic detection and source-location from P waves in real time" (GITEC-2- EU funded, 1995).

2.6- Tsunami sedimentary signature

Tsunamis are major events in terms of the sedimentary record. The enormous quantity of sediments brought inland by tsunami waves are usually contrasting in coastal stratigraphy, usually being coarser (e.g. well-sorted sand, typical of beach and shore deposits, found in layers within marsh, coastal lakes or ponds deposits). Some layers are composed of several upward-fining sequences interpreted to represent successive wave pulses, whereas other deposits are massive. Sand beds also deposited in intertidal and marsh environments by channel migration, river floods and storms, so some criteria are needed to distinguish between tsunami sand and non-tsunami sand (Dawson et al., 1991; Einsele et al., 1996; Nanyama et al. 2000, Pinegina et al., 2003). A series of diagnostic criteria to identify tsunami sedimentary deposits is presented in Chapter 3.

The sedimentary signature of tsunamis translates conditions such as the high-energy depositional conditions, the material available, the coastal geomorphology, the wave behaviour and others. All these characteristics have a decisive contribution to the tsunami sedimentary deposit. However, many questions remain unanswered about the processes of deposition from tsunami.

The research on palaeotsunamis through sediments provides better information on tsunami frequency-magnitudes for given areas.

2.7- Conclusion

Tsunamis are natural catastrophes caused by some geological processes (e.g. earthquakes, landslides, volcanoes, meteors) that disturb a mass of water creating a series of waves. The waves formed, after the geological trigger, travel towards coastal areas and will increase in height with the decrease of their velocity, causing destruction when the tsunami reaches the shoreline. Historically, devastation from tsunamis has been reported since 1410 BC (Greece) (USGS-tsunami datbase).

Tsunami catalogues from different parts of the world (e.g. Lander & Whiteside, 1997; Tinti & Maramai, 1996; Nakata & Kawana, 1993; Iida et al., 1967a, 1967b; Heck, 1947; Papadopoulos & Chalkis, 1984; Zhou & Adams, 1986; NGDC, 1997, 2001) list far more than 2000 tsunami events during the past 4000 years. In Europe tsunami events are rare. The most active tsunamigenic areas in Europe are the Azores area, the Eastern Mediterranean and the Gorringe Bank (200 km SW of the Algarve). Furthermore, the Iberian Peninsula has low frequency of tsunamis. However, the largest tsunami in the Atlantic coasts of Europe was the well-known 1755 tsunami, which followed the Lisbon earthquake.

The understanding of the genesis and impact of palaeotsunamis in coastal areas is crucial to evaluate the tsunami hazard and to prevent the consequences of future tsunamis (Leroy, 2006).

3. Geological Evidence of Tsunamis and Storms

3.1- Introduction

Tsunamis and storms are major threats, especially to coastal areas densely populated. It is important to be able to distinguish storm and tsunami deposits to reconstruct patterns of coastal change and for an accurate assessment of the hazard frequency. The study of sediments deposited by tsunamis is crucial because it will increase the knowledge and understanding of the frequency and magnitude of past events. However, identifying tsunami deposits is a difficult task. Tsunamis are high-energy events that often deposit a coarser sedimentary unit in coastal lagoonal sequences. Tsunami sedimentary deposits are distinctive. Nevertheless, other events such as channel migrations, river floods and storms can cause the deposition of coarser layers in the stratigraphic sequence of a coastal lagoon. The need to clearly distinguish different types of events resulted in a group of characteristics that are summarized in Table 3.1. To some extent the criteria presented are just indicators of a marine invasion. The differences between tsunamis and other natural marine invasion phenomena (e.g. storms, hurricanes) are one of the most controversial subjects when discussing palaeotsunami deposits. It is also interesting to compare sediments from subsidence deposits, during earthquakes, with tsunami deposits. Some of these events have very similar sedimentological signatures and to distinguish them is difficult, but crucial.

Intensive research (e.g. Atwater, 1986; Atwater & Moore, 1992; Atwater et al., 1995; Bruzzi & Prone, 2000; Dawson et al., 1991,1999, 2000, Kortekaas, 2002; Liu & Fearn, 1993, 2000a, 2000b, Nanayama et al., 2000) has been done in this fundamental aspect of how to distinguish tsunamic sedimentary formations from other marine invasive deposits. Tsunamis, however, are major sedimentary events and, usually, its uniqueness is one criteria used (this can only be applied in regions not subject to frequent tsunamis).

However, the problem remains; it is exceptionally difficult to differentiate tsunami deposits from units deposited by storm surges.

Diagnostic Criteria	Type of criteria	Selected references
Sheet of deposits that generally fines inland and upwards	Stratigraphic	*Foster et al. 1991; Dawson 1994*
Each wave can form a distinct sedimentary unit, although this is not often recognised in the sedimentary sequence	Stratigraphic	*Ota et al. 1985; Moore & Moore 1988; Clague & Bobrowsky 1994a, b*
Distinct upper and lower sub-units representing run-up and backwash *can* be identified, but investigation of recent tsunami deposits indicates that there is still considerable uncertainty about when most deposition occurs (during run-up or backwash or in between) and so these sub-units may be related to other processes	Stratigraphic	*Moore & Moore 1988; Dawson et al. 1996*
Lower contact is unconformable or erosional	Stratigraphic	*Dawson et al. 1988; Moore & Moore 1988*
Can contain intraclasts of reworked material, but these are not often reported.	Stratigraphic	*Dawson 1994; Moore et al. 1994*
Often associated with loading structures at base of deposit	Stratigraphic	*Dawson et al. 1991; Minoura & Nakaya 1991*
Particle and grain size range from boulder layers (up to 750 m^3), to coarse sand to fine mud. However, most deposits are usually recognised as anomalous sand units in peat sequences	Granulometric	*Ota et al. 1985; Moore & Moore 1988; Minoura & Nakaya 1991; Dawson 1994; Minoura et al .1994; Young et al. 1996*
Generally associated with an increase in abundance of marine to brackish-water diatoms, but reworking of estuarine sediments may simply produce the same assemblage; preservation of frustules can be excellent, although many are often broken	Palaeontological	*Dawson et al. 1988; Minoura et al.1994; Hemphill-Haley, 1996 Clague et al., 1999*

Diagnostic Criteria	Type of criteria	Selected references
Marked changes in Foraminifera (and other microfossils) assemblages. Deeper-water species are introduced with catastrophic saltwater inundation	Palaeontological	*Patterson & Fowler, 1996; Shennan et al. 1996; Clague et al., 1999*
Individual shells and shell-rich units are often present	Palaeontological	*Moore & Moore 1988; Bryant et al. 1992*
Often associated with buried terrestrial plant material and/or buried soil	Palaeontological	*Clague & Bobrowsky 1994b; Dawson 1994*
Shell, wood and dense debris often found "rafted" near top of sequence	Palaeontological	*Albertao & Martins 1996; Imamura et al. 1997; Clague et al., 1999*
Increases in the concentration of sodium, sulphate, chlorine, calcium and magnesium occur in tsunami deposits relative to under and overlying sediments; indicates saltwater inundation	Geochemical	*Minoura et al. 1994; Goff & Chague-Goff 1999*
Dating tsunamis is problematic "...". Optical dating (OSL) is the best method available *assuming* the sediments were exposed to daylight during reworking by the tsunami. Radiocarbon may date older debris incorporated in the tsunami layer and provide a too old date	Dating	*Dawson et al. 1988; Hamsom & Briggs 1991; Clague & Bobrowsky 1994b; Dawson 1994; Huntley & Clague 1996; Fujiwara et al., 2000*

Table 3.1: Tsunami sedimentary characteristics
(Modified from Goff et al., 1998).

The criteria to identify tsunami deposits can be sub-divided in: stratigraphic, granulometric, palaeontological, geochemical and dating. In the following text these criteria are discussed and some comments are made.

Literature dedicated to geological traces of tsunami is rare when compared with tsunami generation mechanisms, numerical analysis and the physics of the tsunamis. In terms of the sedimentary signature of tsunamis various studies have been conducted especially over the past 20 years (Figure 3.1). The first studies to use geological record to detect prehistoric tsunamis were conducted by Atwater (1987) and Dawson et al. (1988). Since then several papers were published describing tsunami deposits in the geological record. A few of those papers are briefly mentioned in the following text.

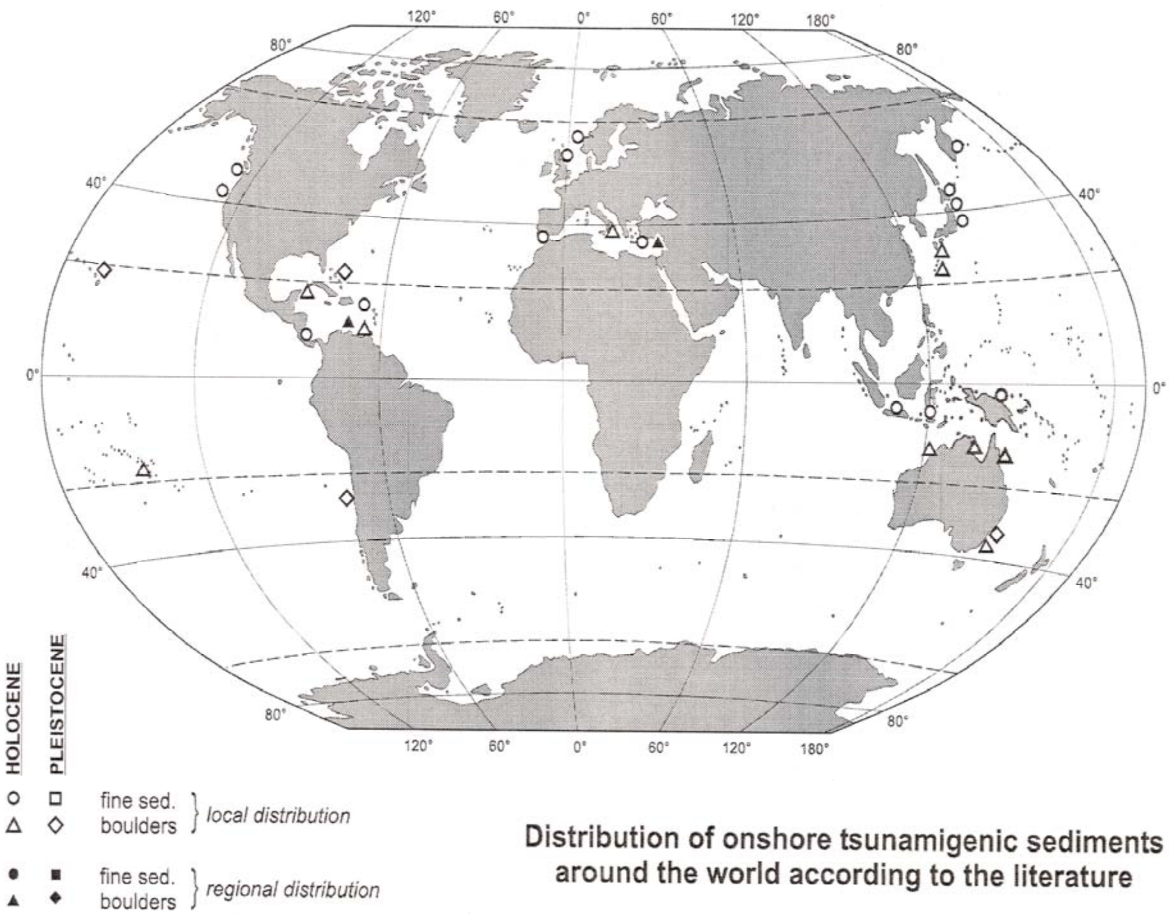

Figure 3.1- Locations with reliable tsunami evidence documented in sedimentary record and/or geomorphological imprints (Scheffers & Kelletat, 2003)

3.2- Stratigraphic criteria

The most obvious evidence of a tsunami deposit is its signature in coastal stratigraphy. However to obtain an accurate representation of the effects of a tsunami, intense field work is required. Assessment of spatial distribution of a tsunami requires cross-sections or drilling cores across the area of the tsunami (Scheffers & Kelletat, 2003) and correlation between them. Although sedimentological studies of palaeotsunamis developed recently (over the past 20 years), there is abundant literature on the interpretation of tsunamigenic deposits both of Holocene and older ages. Some representative studies on Holocene tsunami deposits concern, for instance, the Storegga megaslide ca. 7000 years BP (Dawson et al., 1988, 2000; Bondevik et al., 1997) or the collapse of the Santorini volcano ca. 3500BP (Kastens and Cita, 1981; Cita and Rimoldi, 1997). Furthermore, around the world various studies using (directly or indirectly) the stratigraphic signature of tsunami deposits have been conducted (Table 3.2).

Region	**Selected References**
Iberian Peninsula	Andrade, 1992; Dawson et al., 1995; Hindson et al., 1996; Dabrio et al., 1998;Luque et al, 2001; Kortekaas, 2002; Scheffers & Kelletat, 2005
Europe	Dawson et al., 1988; Long et al., 1989; Foster et al., 1993; Bondevik et al., 1997; Dawson & Smith, 2000
Mediterranean Sea	Papadopoulos & Chalkis, 1984; Antonoupolous, 1992; Dominey-Howes, 1996 a, 1996 b; Mastronuzzi & Sanso, 2000; Kortekaas, 2002
North America	Atwater, 1987; Atwater & Moore, 1992; Clague & Bobrowsky, 1994 a, b; Clague et al., 1994; Benson et al., 1997; Hutchinson et al., 1997; Clague et al., 1999
Central America	Bourgeois, 1993
South America	Atwater et al., 1992
Caribbean	Scheffers & Kelletat, 2002
Japan	Minoura & Nakaya, 1991; Nakata & Kawana, 1993, 1995; Minoura et al., 1994; Sato et al., 1995; Fujiwara et al., 2000; Nanayama et al., 2000

Region	Selected References
New Zealand	Goff et al., 1998, 2000; Chagué-Goff et al., 2002
Australia	Bryant et al., 1992; Young & Bryant, 1992; Bryant et al., 1996, 1997; Bryant & Nott, 2001
Hawaii	Moore & Moore, 1988; Felton et al., 2000
Indonesia	Shi et al., 1995; Dawson et al., 1996; Minoura et al., 1997

Table 3.2- Selected studies of tsunami deposits around the world

Tsunami deposits generally display landward thinning which results from the decrease in energy with the penetration in land of the tsunami waves (Figure 3.2). Another feature that is often detected in tsunami deposits is that the unit tends to fine upwards (Figure 3.2). Dawson et al. (1988) suggested that stacked fining-up sequences within a sand layer from the Storegga event could be used to characterise the tsunami. Another stratigraphic characteristic of tsunami deposits is presence, although not frequent, of sub-units formed by each wave or by the run-up and the backwash (Figure 3.2). For instance Luque et al. (2002) noted that a single tsunami may involve several closely-timed events of swash and backwash, from either the same wave or several successive waves.

An additional stratigraphic feature in tsunami deposits is the presence of an erosional contact (Figure 3.2). Bondevik et al. (1997) recorded greater erosion in the seaward portions of basins than in the landward portions.

Moreover, also frequently detected in tsunami deposits are loading structures and intraclasts of reworked material (Figure 3.2). The presence of loading structures demonstrates the considerable amount of sediments deposit by the tsunami waves. The presence of intraclasts within the tsunamigenic unit demonstrates the effects of erosion, suspension and re-deposition of sediments that were part of the pre-event stratigraphic column.

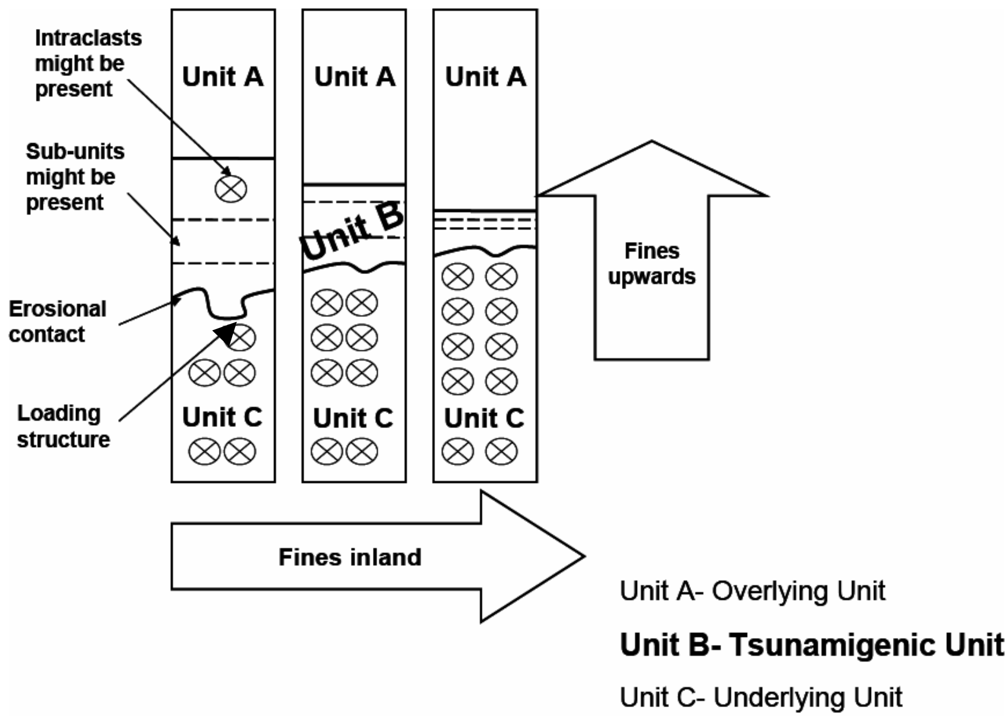

Figure 3.2- Schematic representation of lithostratigraphic characteristics of tsunami deposits.

However, not only in coastal areas sedimentological traces of palaeotsunamis can be detected. Submarine sediments have been attributed to tsunamis (e.g. Keller et al., 1994; Smit et al., 1992, 1994). Furthermore, Kastens & Cita (1981) and Cita et al. (1984) described the western Mediterranean Sea contains a distinct acoustically recognised deposit of structureless muds and silts, with a fining-up character, interpreted by those authors as resulting from a large tsunami.

In conclusion, the stratigraphic criteria illustrate the uniqueness of the unit deposited by the tsunami. Moreover, the stratigraphic criteria also represents the high-energy and abruptness of the event. The unit deposited by tsunamis is, usually in strong contrast with the underlying and overlying units, representing the exceptional character of tsunami deposits in coastal stratigraphic.

3.3- Granulometric criteria

An untrained observer may only suspect of a tsunami deposit if clearly wave-induced sediments are located inland or very coarse material is observed. According to Bryant and Nott (2001) tsunami events are capable of transporting sand and other fine materials even at 30 km inland at sites along the Australian west coast. However, the granulometric criteria demonstrate that although capable of transporting coarser material, the tsunami deposit will consist of the material available in the near-shore area. Furthermore, according to Einsele et al. (1996), "The pre-event sediment accumulation and specific characteristics of the site of intermediate sediment storage clearly are prerequisites for the subsequent depositional event". To conclude, coarser as well as fine material might be identified as a tsunami deposit.

The following list by Scheffers and Kelletat, (2003) shows that *45%* of the literature on tsunamis involves the study of fine-grained sediments: Dawson et al. (1988); Long et al. (1989); Darienzo & Peterson (1990); Minoura & Nakaya (1991); Andrade (1992); Atwater (1992); Bourgeois (1993); Yeh et al. (1993); Clague et al. (1994); Minoura et al. (1994); Sato et al. (1995); Shi et al. (1995); Bondevik (1996); Hindson et al. (1996); Clague (1997); Moya (1999); Clague et al. (2000); Dawson & Smith (2000), while analyses of boulders make up to *55%* of literature: Davies & Hughes (1983); Miyoshi et al. (1983); Moore & Moore (1984), (1988); Bourrouilh-Le Jan & Talandier (1985); Ota et al. (1985); Harmelin-Vivien & Laboute (1986); Talandier & Bourrouilh-Le Jan (1988); Paskoff (1991); Bryant et al. (1992), (1996); Jones & Hunter (1992); Jones (1993); Nakata & Kawana (1993), (1995); Shi et al. (1993), (1995); Moore et al. (1994); Nishimura & Miyaji (1995); Schubert (1994); Bryant et al. (1996); Hearty (1997); Nott (1997), (2000); Mastronuzzi & Sanso (2000); Felton et al. (2000); Kelletat & Schellmann (2001), (2002); Scheffers, (2002a), (2002b).

In conclusion, tsunami deposits can be formed by fine sediments (clay, silt, fine sand) or by coarser sediments (coarse sand or boulders), depending on the material available in the coastline (e.g. Figure 3.1).

3.4- Palaeontological criteria

Marine to brackish fauna and flora are brought inland by tsunami waves. The waves transport not only sediments but also material that will be fossilised (when deposition occurs) within the tsunamigenic unit. The palaeontological criteria have been increasingly used in the identification of tsunami deposits (Table 3.3). Macrofossils and microfossils have been used to identify and interpret some units as tsunamigenic. So far, the use of palaeontological characteristics to recognise tsunami deposits has focused on diatoms, foraminifera, ostracods, molluscs and plant fragments (Table 3.3).

The palaeontological criteria indicate not only the high-energy of the event (e.g. presence of roots, plant fragments, broken shells, etc) but also the increase in abundance of marine to brackish fossils. The palaeontological criteria also rely in specific hydrologic and geodynamic conditions. In fact depending of the hydrodynamic of the shoreline, the geomorphology of the coast and the behaviour of the tsunami waves, the fossil record will present particular/different characteristics. The palaeontological assemblages depend, for example, on the habitats crossed by the tsunamis waves when travelling towards the coast.

Generalisations of the palaeontological criteria are difficult. For instance, within a tsunami deposit one might detect brackish diatoms as well as deep water foraminifera. It is important to contextualise the fossils detected with the species found off-shore and with the palaeontological record of the underlying and overlying units.

Palaeontological criteria can be used to identify the source of the fossils/sediments deposited by a tsunami. However, it is not conclusive when used *per se* in the distinction between different types of marine invasions. Undoubtedly, an important proxy, the palaeontological criteria cannot be used as a unique proxy to identify and differentiate units deposited by abrupt marine invasions. Moreover, palaeontological criteria should be applied in most, if not all, palaeotsunami studies but always in conjunction with other proxies.

Fossil	Selected Reference
Diatoms	Hutchnison et al., 1992; Minoura & Nakata, 1994; Minoura et al., 1994; Hemphill-Haley, 1995, 1996; Bondevik et al., 1996; Dawson et al., 1996; Goff et al., 1998; Clague et al., 1999; Dawson & Shi, 2000;
Foraminifera	Hutchnison et al., 1992; Minoura et al., 1994, 2000; Hemphill-Haley, 1996; Bondevik et al., 1996; Dominey-Howes, 1996a, 1996b; Guilbault et al., 1996; Hindson et al., 1996, 1999; Clague et al., 1999; Kortekaas, 2002
Ostracods	Fujiwara et al., 2000
Molluscs	Minoura et al., 1997; Fujiwara et al., 2000
Plant fragments	Atwater & Yamaguchi, 1991; Clague & Bobrowsky, 1994a, 1994b; Benson et al, 1997; Hutchinson et al., 1997, 2000; Clague et al., 1999

Table 3.3- Palaeontological studies in tsunami deposits
(Adapted from Kortekaas 2002)

3.5- Geochemical criteria

The chemical signature left by marine sediments in the stratigraphic column is a subject recently explored in the study of palaeotsunamis.

Recent studies (Minoura & Nakaya, 1991; Minoura et al., 1994; Andrade & Hindson, 1999; Goff & Chagué-Goff, 1999; Walters & Goff, 2003) confirmed that geochemistry may become increasingly important in the identification of tsunami events that leave small stratigraphic evidences or to detect tsunami deposits further inland (where no stratigraphic evidence is registered).

As mentioned previously, tsunami deposits are formed according with the material (e.g. sediments) available in the coastline and brought inland by the tsunami waves. Each type of sediment that composes a tsunami deposit will have its own characteristic chemical composition. It is obvious that the chemical signature of the tsunami deposit will reflect the sedimentary composition (Table 3.4).

Geochemical signature	**Sedimentological and hydrological features**	**Selected References**
Increase in concentration of Cl, Na, SO_4, Mg, Ca and K	Present in most marine sediments (the major salt elements)	Newson (1979)
Increase in Na, Ca, K, Mg and Cl	Indicate marine origin of sediments	Minoura & Nakaya (1991)
Increase in Cl, Na, Ca, SO_4 and Mg	Components of seawater and carbonates (due to the influx of biogenic marine carbonates)	Minoura et al. (1994)
Increase in SiO_2, CaO, Cr, MgO, I and Cl	Presence of siliceous sand, carbonate bioclasts and marine invasion	Andrade & Hindson (1999)
Increase in Fe and S and dilution of anthropogenic elements	Increase in fine sediments (clay and silt)	Goff & Chagué-Goff (1999)

Table 3.4- Major geochemical signature in tsunami deposits

The tsunami deposit chemical signature should be compared with the underlying and overlying units and changes should be detected (e.g. increase in major salt elements, etc.; Table 3.4). In conclusion, the geochemical criteria prove the marine origin of the deposit and/or reflect its sedimentary composition. Furthermore, an increase in the use of geochemistry as an important research proxy will facilitate the task of identifying tsunami deposits.

3.6- Dating tsunami sedimentary units

Dating tsunami deposits is complicated. Tsunami units incorporate older sediments that are available in the coastline when the waves approached the coast. Because of that fact an overestimation of the age can be obtained. Furthermore, due to the depositional and erosional characteristics of tsunamis (both runup and backwash can erode and deposit sediments) a tsunamic unit is compose of a mixtures of sediments, making it possible to obtain very different ages inside the deposit and, obviously complicating the accurate estimation of the age of the deposit. However, it is crucial to obtain accurate dates for tsunami units. References of methods used to obtain dates of tsunami deposits include radiocarbon dating (most widely used), the use of ^{210}Pb and ^{137}Cs, the use of tephra chronology and luminescence dating (e.g. Optically Stimulated Luminescence and Thermoluminescence). The selection of the appropriate dating technique is dependent on the age expected for the event, the material (e.g. sediments and fossils) available and the geological setting of the study area. An indirect date for a tsunami deposit might be obtained if underlying units (many times eroded by tsunami waves) or overlying units are dated, and then the age expected for the event is constrained to a more precise interval.

3.7- Differentiating tsunami and storm sedimentary deposits

Coastal areas are subject to high-energy events (e.g. storms surges, typhoons, hurricanes, tsunamis). Even with different recurrence times those events clearly affect the local stratigraphy and geomorphology. The high energy involved is capable of transport and depositing large quantities of sediments. Storm waves are generally destructive and lead to the removal seaward of large quantities of sediment. Tsunamis are low-frequency high-magnitude events capable of deposit a sedimentary signature.

The influx of materials in coastal areas has different sources. "A wave dominated shallow-marine system consists of an assemblage of depositional environments" (Swift et al., 1991; Thorne & Swift, 1991) compromising coastal plain, lagoon, washover, shoreface (proximal and distal), and shelf.

The contribution of specific abrupt events to the geological and stratigraphical record is significant. Sedimentary events deposits occur in both continental and marine environments (Table 3.5).

Marine	Marine and Continental	Continental and lacustrine
Tsunami deposits (submarine and coastal)	*In-situ* earthquake structure (seismites)	Flood deposits
Storm deposits, supratidal	Volcanic ash fall deposit	Lacustrine turbidites
Tempestites, subtidal (siliciclastic and biogenic sand and mud)	Deposits caused by meteorite impacts	
	Rockfall, slide and slump deposits	
Turbidites (siliciclastic and biogenic sands, silts and muds, with organic mud; volcanic ash)	Sediment gravity flow deposits (mud, grain, debris, pyroclastic flow deposits, olistostromes)	

Table 3.5- Types of event deposits (Einsele et al., 1996)

According to Einsele et al. (1996), "most events represent redeposited material which has accumulated earlier along basin margins. (…) several phases in the generation of event beds can be distinguished" (Figure 3.3).

The mechanism associated with the deposition of any sedimentary unit associated with an event follows a four stage order (pre-event accumulation; event; transport; redeposition). The first stage consists in the sedimentary accumulation before the event (pre-event accumulation); the second phase includes the triggering of the event and the event itself (event); the third phase involves the transport of the sediments after the event (transport); the four and final phase consists in the deposition of the event bed (redeposition). Moreover, transport of sediments in shallow-marine environments is governed by local hydraulic regimes, which can be described on many temporal scales. In Figure 3.3 the processes involved in the generation of event deposits are presented.

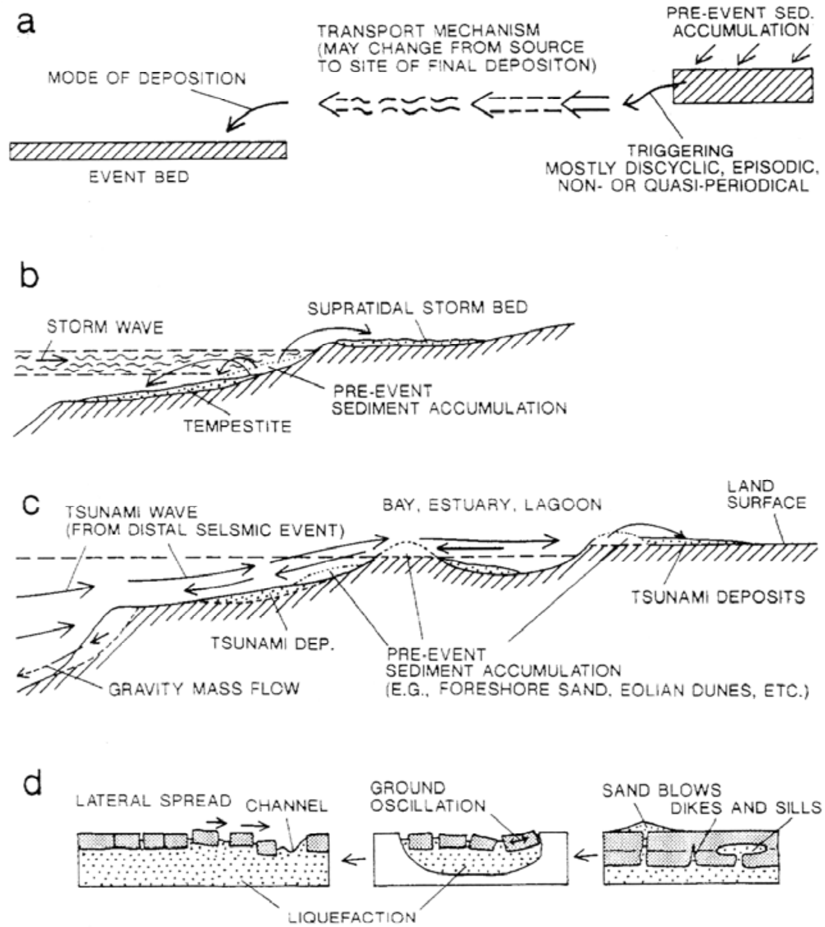

Figure 3.3- Processes involved in the generation of event deposits

(Einsele et al., 1996)

Figure 3.3a- Scheme of event beds resulting from redeposition of sediment accumulated prior to the event.

Figure 3.3b- Supratidal storms layers and subtidal tempestites consisting of pre-event sediments accumulated in the foreshore zone.

Figure 3.3c- Deposition of sediments after an earthquake-induced tsunami. Deposition may occur from both the landward flow and backflow as well as submarine slope failure. Tsunami deposits consist mainly of pre-event sediment of the foreshore and coastal zones.

Figure 3.3d- In-situ disturbances of flat-lying pre-event sediments by earthquake shocks (after Greene et al., 1994).

Despite recent developments in the differentiation of abrupt marine invasions, unequivocal criteria for distinguishing between deposits of storms and tsunamis have yet to be developed.

Darienzo & Peterson (1990) noted the fact that "in open coastal settings, deposits produced as a result of infrequent storm surges are often difficult to distinguish from those due to tsunamis". However, in some specific locations it has been possible to differentiate tsunami and storm deposits. Over the last decade a considerable number of papers (e.g. Foster et al., 1991; Dawson, 1994, 1999; Shi 1995; Einsele et al., 1996; Nelson et al., 1996; Clague & Bobrowski, 1999; Nanayama et al., 2000; Kortekaas, 2002; Pratt, 2002; Tuttle et al., 2004) addressed the problem of distinguishing tsunami and storm deposits. Although the physics of the tsunamis and storms are different (for instance the wavelength), the geological signature is very similar, if not the same. Furthermore, "Unlike storm surges individual tsunami waves reach a point of zero velocity prior to backwash flow. At this point large volumes of sediment may be deposited out of the water column and onto the ground surface" (Dawson, 1999). Moreover, all tsunamis produce local acceleration and deceleration of the water column. Tsunamis are abrupt events and normally will not last longer to permit the formation of wind waves (in contrast with storms).

The geological comparison of tsunami and storm deposits is critical. Nanayama et al. (2000) conducted research on deposits that resulted from the 1993 Hokkaido-nansei-oki tsunami and from the 1959 Miyakojima typhoon (Table 3.6). A trench with 3 metres wide, 9 metres long and 1.5 metres was excavated in 1996. Furthermore, multiple layers of the 1993 tsunami deposits were detected. The tsunami deposits were as much as 35 cm thick. At the deeper end of the trench a storm deposit was detected with 50 cm thickness. Both deposits present landward thinning. Major characteristics of the 1993 tsunami and 1959 storm deposits are presented in Table (3.6).

Event	Sedimentary facies	Thickness (cm)	Flow direction	Grain composition
1993 Tsunami deposits	Four Layers	Lenticular ~45; Thinning landward	Upflow and return flow for two waves	Upflow deposits: mostly marine and with rounded gravel and seashell; Return flow: mostly non-marine sand with soil and plant fragments and stream gravel
1959 storm deposit	Single Layer	Lenticular ~50; Thinning landward	Only landward flow	Mostly marine sand; better sorted

Table 3.6- Major characteristics of the 1993 tsunami and 1959 storm deposits
(Adapted from Nanayama et al., 2000)

In the Scilly Isles, Dawson et al. (1991) also detected a tsunami deposit. Moreover, the tsunami deposit was attributed to the AD 1755 tsunami. However many similarities were established by the authors with possible storm deposits found in the same location (Big Pool, St Agnes).

Bryant (pers. comm., 2002) studied cliffs along the New South Wales coast, in Australia and concluded that tsunami may deposit well above extreme cyclone wave limits. Moreover, Bryant (pers. comm., 2002) referred that "many of these features have been attributed, without substantiation, to long-term erosion by wind-generated waves. However, some features lie beyond the reach of normal or high-energy wave attack and bear similarities to features carved by enormous floods that were last present on Earth during the Last Ice Age".

Williams & Hall (2004) demonstrated that megaclasts ridges of western Ireland and northern Scotland form a record of extreme storm generated wave activity in the region. It is also important to note that this study focused in cliff tops that do not have a sediment matrix. An interesting conclusion of Williams & Hall (2004) is that "it is unlikely for example that isolated tsunami events will have greater effect on the general morphology of coastlines than persistent storm activity, one of the primary controlling factors of coastal recession". This remark stresses the underrated importance of storm surges to coastal geomorphology. However, it is important to state that although tsunamis are rarer, the effects they leave in coastal geomorphology cannot be underestimated (e.g. Bryant et al., 1996).

Kortekaas (2002) also detected tsunami and storm deposits in the same location, Martinhal, in the Algarve, Portugal. This research will be discussed in more detail in chapter 7. The main conclusion of Kortekaas (2002) is that tsunami and storm deposits (as well as coseismic subsidence) have very similar geological characteristics and that only a multi-proxy approach might allow the distinction between tsunami and storm deposits.

Palaeotempestology is the study of prehistoric storms. Nott (2004) suggests that "patterns and periodicities of prehistoric storms can be reconstructed from sediments, organic and lithic, deposited by surge and waves at elevations or distances inland beyond the reach of normal marine processes. Erosional terraces can also be left in the landscape by the same processes". The study of storm surges deposits allows a more complete assessment of the hazard risk for a specific coastal area.

Bussert & Aberhan (2004) detected tempestites in southeastern Tanzania characterised as "poorly sorted conglomeratic sandstones with megaripple surfaces. The fine-grained sediments filling the ripple troughs most probably formed during the cessationof the storms, when stirred up fines settled out of suspension". The authors also noted that the absence of articulated bivalves, size sorting and the hydrodynamically stable convex-upposition of most shells indicates post-mortem transport and the influence of currents at the time of deposition.

In the coast of New Jersey, Donelly et al. (2004) detected a series of sand overwash fans deposited within estuarine sediments that were transported into the estuary by storm surge and waves. This overwash fans were composed by very-fine-to-fine, well-sorted sand units; the abrupt nature of the lower contacts and lateral continuity of these sediments also indicated the evidence of soft sediment deformation in adjacent muds. In this study correlation with historical documents was possible however.

Finally, and based on previous research, one might conclude that tsunamis and storms have very similar geological signatures; differentiating them (if it is possible) might be more likely in specific locations and having in consideration local aspects (e.g. historical records, sedimentology, geomorphology and hydrodynamics). A greater penetration inland and “lateral translation of water across the coastal zone” (Dawson et al., 2004) are expected in tsunami waves; in conclusion, one might expect the presence of tsunami deposits in a larger area (further inland and further along the coast) when compared with storm deposits.

3.8- Conclusion

Geological evidences of tsunami and storms (in a broader approach one might say abrupt marine invasions) are crucial to understand and predict patterns of coastal flooding. Despite the fact recent developments in tsunami sedimentary research brought new and more precise approaches to the study of tsunamis deposits, the development of standard criteria of identification and field methods to clearly recognise tsunamis and distinguish them from other abrupt events is, still, an uncompleted task.

The group of criteria presented in this chapter is commonly accepted has sufficient to identify abrupt marine invasions in coastal stratigraphy (e.g. coastal lakes, estuaries, etc). Due to their specific conditions (concerning deposition, erosion, biodiversity, salinity, etc.) coastal lakes are preferential locations for palaeoseismological and palaeoenvironmental research.

The key challenge in the recognition of tsunamis in past sedimentary records is separating a distinctive signature of the tsunami from other abrupt sedimentary processes.

4- The AD 1755 Tsunami

4.1- Iberian Peninsula

Tsunamis are not frequent in Europe, although some coastal regions of the Mediterranean and of the Atlantic have been struck by tsunami events. "The most prominent regions struck by tsunamis in the European area are the coasts of insular Greece, in the Eastern Mediterranean and the coast of southern Italy, in central Mediterranean" (Moreira, 1988). The eastern Mediterranean is the region of Europe where most tsunamis have been detected (Cita and Rimoldi, 1997). Although in terms of magnitude the most important tsunamigenic zone of Europe, is the Gorringe Bank located at 200 km Southwest of Cape Saint Vincent. It is also the main tsunamigenic zone that affects the Iberian Peninsula. This bank is located in the eastern part of the "Azores-Gibraltar Line, the western boundary between the African and Eurasian Plates, which runs roughly E-W connecting the Azores triple junction to the Gibraltar Strait" (Zitellini et al., 1999). It is positioned between the Tagus Plain, to the North, and the Horseshoe Plain, to the South. The Gorringe Bank is also the most likely location of the 1755 earthquake. However there are five proposed locations for the AD 1755 epicentre (Figure 4.1).

The Iberian shores are, fortunately, rarely affected by tsunamis. Despite the huge tsunami of AD 1755 and its consequences in terms of human lives, both the Atlantic and the Mediterranean coasts have scarce historical literature of tsunami hazards. Nevertheless a few events deserve special notice (Figure 4.2).

There is a strong link between seismological activity and tsunami generation. The Iberian Peninsula is not an exception. According to Campos (1991) in the Iberian Atlantic coasts, one can consider three main seismotectonic areas and, as a consequence, three main tsunamigenic areas. "Zone A - from the Mid-Atlantic ridge to 25 ^{o} W. It is an area of expansion of the oceanic crust because of the mid-Atlantic ridge. It is unlikely that it would generate tsunamis, because earthquakes are of small magnitude and their focal mechanism solution is not associated with vertical displacement. Zone B – from the Gloria fault (24 ^{o} W) to 18 ^{o} W. It is an area of friction where large-magnitude earthquakes occur, that are however associated with dextral horizontal displacements along a fault orientated E-W (Udias et al., 1985). This kind of displacement generates small tsunamis that are not generally observed on the South-western coast of the Iberian Peninsula.

Zone C – The Cadiz Gulf is the main source of tsunamis. This is a zone of intense interaction between the African and the Eurasian plates that undergo strong deformations in approaching and compressing. The most important tsunamis were generated in that area, located from 12° to 6°W along the 36 °N parallel (which includes the Gorringe Bank). Possibly, the 1755 earthquake had its epicentre in this area."

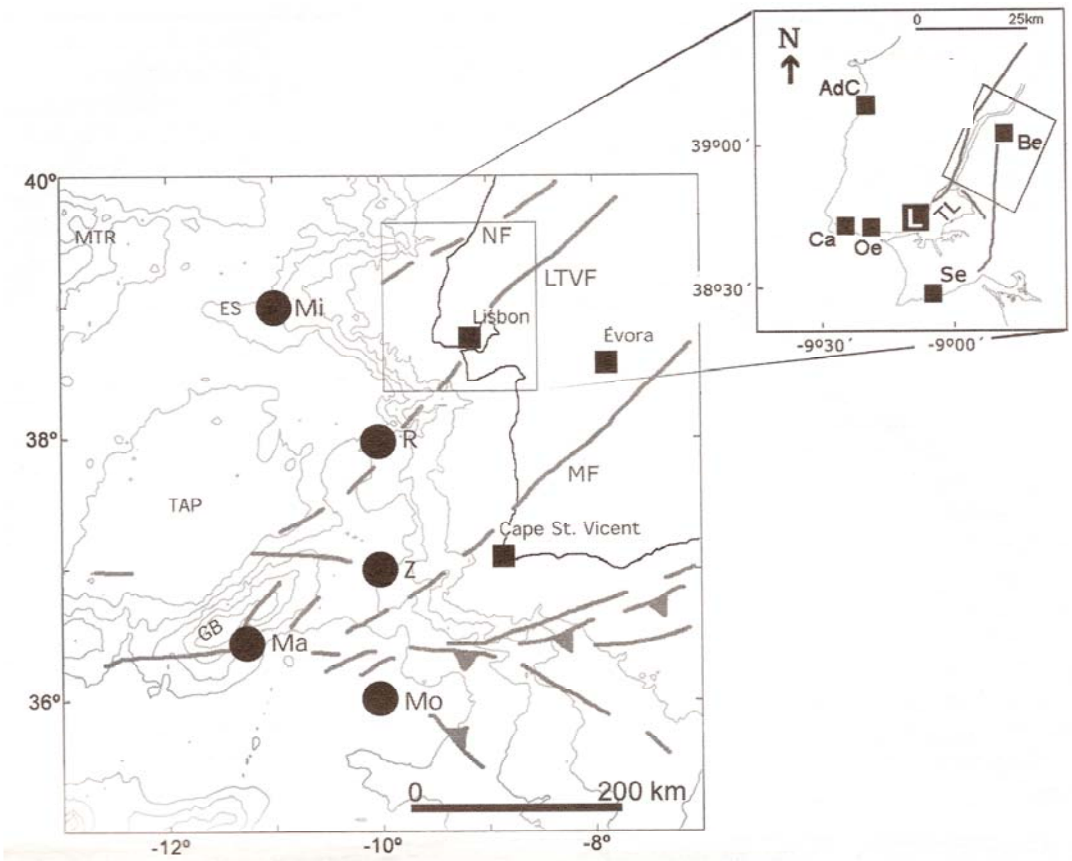

Figure 4.1 –Possible epicentres locations (black circles) for the AD 1755 earthquake (Vilanova et al., 2003)

Structural features according offshore according to Buforn et al. (1995). Lower Tagus Valley Fault (LTVF) and associated structures (inset) according to Fonseca & Long (1991).

Mi, D.Milne cited by Johnston (1996); ***R***, Reid (1914); ***Ma***; Machado (1966); ***Mo***, Moreira (1989); ***Z***, Zittellini et al. (1999).

NF, (Nazaré Fault); ***MF***, Messejana Fault; ***GB***, Gorringe Bank; ***TAP***, Tagus Abyssal Plain; ***ES***, Estremadura Spur; ***MTR***, Madeira-Tore Rise (shown at its northeast termination); ***L***, Lisbon; ***AdC***, A-dos-Cunhados; ***Be***, Benavente; ***Ca***, Cascais; ***Oe***, Oeiras; ***Se***, Sesimbra; ***TL***, Tagus lagoon.

In the Mediterranean coasts of Iberia, tsunami generation is caused by local factors. “The small earthquakes occurring in the Western Mediterranean do not generally produce tsunamis that can be observed on the Spanish shores, and those known in historical times, according to historical sources are dubious.” (Galbis Rodriguez, 1932). Therefore, “the mechanism that generates Mediterranean tsunamis is closely related to landslides, rockfalls and turbidity currents in the submarine unconsolidated sediments, as a consequence of earthquakes on land, although the actual mechanism is still under discussion” (Campos, 1991).

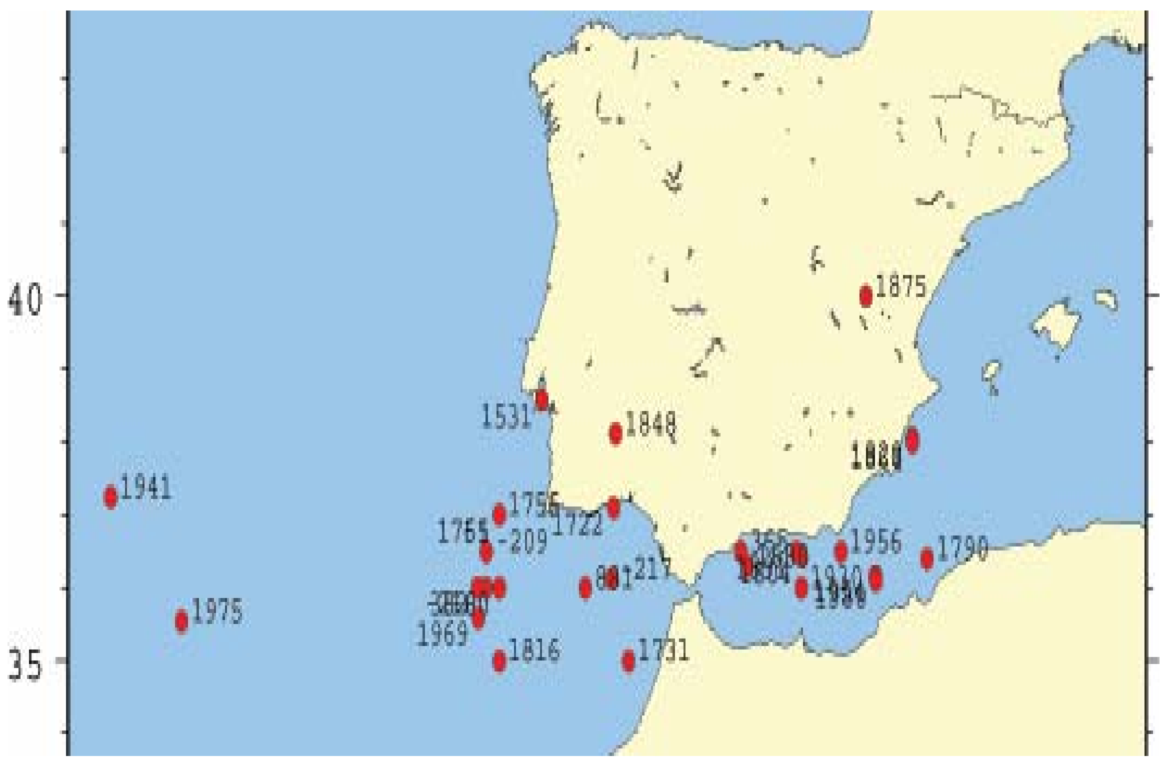

Figure 4.2 – Tsunami earthquake epicentres in the Iberian Peninsula since 217 years BC (Costa et al., 2003)

“The documentary record demonstrates that the most destructive high-energy events of coastal flooding that affected the Portuguese coast in the last millennium are related to seismic activity of the ocean floor” (Andrade & Freitas, 2000). Moreover, “we can conclude that the seismic events generating destructive tsunamis are located inside a box, centred in a geographical longitude position 10 ^{o}W, latitude 35.5 ^{o}N." (Simoes et al., 1992) (Figure 4.3). "The earthquakes taking place 18 ^{o}W towards the Azores Islands, according to available information, produce small size tsunamis hardly observed in the Spanish coasts, though their effects can be felt in the Azores and the Madeira Islands, and even on the coasts of Morocco." (Moreira, 1968).

4.2- Consequences of the AD 1755 Tsunami

The consequences of the Lisbon AD 1755 tsunami are very well known on the basis of historical documents. Furthermore, some older tsunamis have been studied in conjunction with archaeologists.

All over the World the consequences of tsunamis have been studied and the social, cultural and economic importance of tsunamis and its consequences are evident.

A huge earthquake (and tsunami) also affected Lisbon in AD 1531. Although the historical data available is scarce, it is considered a very destructive earthquake also. "In January 1531, the Tagus River Estuary was hit by a strong earthquake, the intensity of which in Lisbon was, according to relevant authors, greater than that of the 1755 earthquake." (Justo & Salva, 1998). The most devastating earthquake and tsunami to strike the Iberian coasts, in historical times, remains the AD 1755.

The 1755 earthquake had a probable magnitude of 8.5 and lasted for ten minutes. The tsunami followed the earthquake, reaching "Cape Saint Vincent in 15 minutes, Lisbon in 30 minutes, Cadiz in 78 minutes, Huelva in 50 minutes, Oporto in one hour, Madeira in 90 minutes and Safi in 30 minutes", after the shake (Baptista et al., 1998b).

Especially Lisbon was devastated by the earthquake and by the tsunami. Fires ravaged through the city. The downtown was flooded, causing vast destruction (e.g. Figure 4.3). It should also be noted that there is the possibility of offshore slumps and slides having contributed for the hydrodynamic of the tsunami waves, especially in the Lisbon area.

"Almost all geophysical studies of the 1755 event rely on the comparison with the 28/02/1969 earthquake that had its epicentre on the Horseshoe Abyssal Plain (36.01 ^{o}N, 10.57 ^{o}W) south of the Gorringe Bank. This comparison is justified by the acceptance of a return period of about 200 years for the earthquakes generated in the SW of the Iberian area." (Baptista et al., 1998 a).

Figure 4.3: Saint Paul's Church after the earthquake
Original painting in City Museum, in Lisbon, (Dinis, pers. comm.2002.)

In 1755, Lisbon was one of the most beautiful cities in Europe. Conquered to the Moors in 1147, it was kept under Moorish influence during the Middle Ages and Renaissance. With an estimated population of 275,000, Lisbon was, in 1755, one of the largest cities in Europe. The tsunami effects were astonishingly destructive. "The death toll directly caused by the tsunami wave in Lisbon was of around 900 people" (Baptista et al., 1998a). The catastrophic succession of events was responsible for, probably, more than 50000 dead in Portugal. In Spain there are reports of more than 1000 people who died as a direct consequence of the tsunami. The cities of Cadiz and Huelva were amongst the most damaged. In Morocco, although the historical data is scarce, there also reports of vast destruction (Levret, 1991; El Alami & Tinti, 1991). The effects of the tsunami were felt over the Atlantic.

There are several historical documents, such as paintings, reports, describing the devastation caused by the earthquake and by the tsunami. The work of Pereira de Sousa (1919) based on Parochial Archives is especially important to understand the sequence of events and its consequences. After the earthquake the Prime Minister Marquês de Pombal sent a questionnaire to all the priests in all parishes in Portugal. Moreover, in the British Society, several *British Accounts* on the 1755 earthquake have been preserved. Also the City Museum in Lisbon has a vast collection about the 1755 events. A vast number of documents produced at the time are now available in Lisbon at the Torre do Tombo National Archive (as the Arquivos do Ministério do Reino) and in the City Museum.

After the cataclysm, the long process of rebuilding the city of Lisbon began led by the Prime Minister Marquês de Pombal. A "morphological break (…) took place when the mediaeval spatial pattern was modified by the reconstruction of the city centre by Pombal, the King's minister responsible for the reconstruction of the city" (Heitor et al., 2000).

The devastation caused by the earthquake lasted several years and its effect in Europe was also important. "The shock waves of the earthquake placed a temporary brake on the emerging rationalism of the European Enlightenment and attempts to explain the disaster in terms of human sinfulness coloured many contemporary accounts" (Chester, 2001). Furthermore, "in the philosophical field this event had a strong impact on the anti-optimism movement by thinkers such as Kant and Voltaire (e.g. Poème sur le désastre de Lisbonne (1756), Candide ou l'optimisme (1759))" (Baptista et al., 1998a).

In conclusion, the consequences of the 1755 were amazingly profound, not only in terms of human lives and infrastructures, but also in terms of architectural, cultural, social, historical and political aspects. Although having been a matter of intensive scientific research the 1755 events are still surrounded by uncertainties.

The run-up height was calculated by historical reports and data, and by modelling (Baptista et al, 1998 a, b). Historical data sometimes tend to exaggerate events. Geological (sedimentological) research over the 1755 tsunami represents a useful alternative source of information. At the present, some results have come from not only in Portugal, more precisely in the Algarve, (Andrade et al., 1992, 1997; Hindson, 1996, 1999a, 1999b; Kortekaas 2002), but also in the Southwest coast of Britain, more precisely in the Isles of Scilly (Dawson et al., 1991; Foster et al., 1993), or in Spain, more precisely Cadiz (Luque et al., 2001).

4.3- Previous studies on the AD 1755 Tsunami

The 1755 tsunami sedimentary signature has been studied in the Algarve (South coast of Portugal), in Cabo da Roca (western coast of Portugal), in Cadiz Gulf (South western coast of Spain) and in Scilly Isles (South of the United Kingdom) (Figure 4.4).

In the Scilly Isles, United Kingdom, Dawson et al. (1991) describes a sand unit attributed to the AD 1755 tsunami. The overlying and underlying units were dated using radiocarbon dating and, later the complete stratigraphic column was dated, by Banerjee et al. (2001) using Optically Stimulated Luminescence. Results differ, while the radiocarbon dates are quite accurate (although caution should be exercised in the interpretation due to the Suess Effect) and confirmed the unit as probably deposited by the AD 1755 tsunami; the Optically Stimulated Luminescence dates were complex and will be discussed in Chapter 6 and 7.

The stratigraphy was described, particularly for the Big Pool, St Agnes, cores. The authors, using grain size and stratigraphical analysis, indicate the AD 1755 tsunami as the probable responsible for the deposition of a sand layer (15 to 40 cm thick).

Figure 4.4- Locations of recognised AD 1755 tsunami deposits

1- Scilly Isles; **2**- Ria Formosa; **3**- Boca do Rio; **4**- Cadiz; **5**- Martinhal; **6**- Cabo da Roca

(for details and references see following text)

Andrade (1992) also recognised tsunami deposits in Ria Formosa, central Algarve. He attributed to the AD 1755 earthquake the severe damage of the barrier chain at Ria Formosa, leading to the drawning and amputation of its oriental extremity and to the extensive overwash of two of the eastern barrier islands (Armona and Tavira). Moreover, Andrade (1992) refers to "morphological analysis of the backbarrier surface of these two islands reveals a unique pattern, compatible with the exceptional overwash event and with the drainage network reorganization process that must have followed the AD 1755 tsunami".

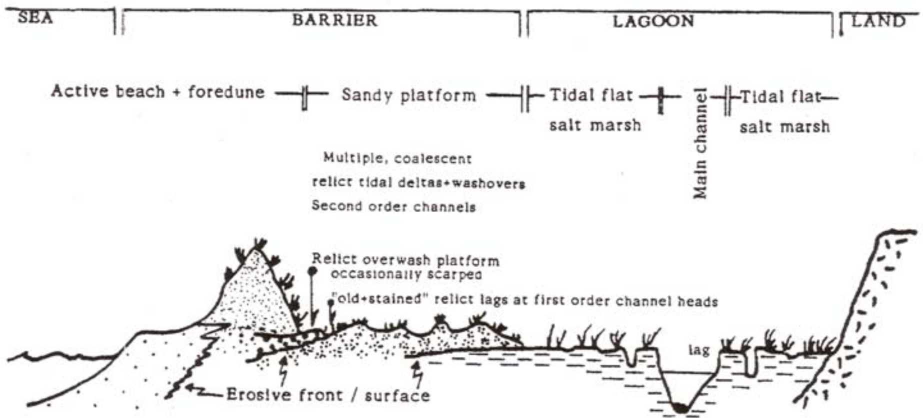

Figure 4.5- Proposed schematic cross section at Ria Formosa (Andrade, 1992)

In the Algarve Hindson and Andrade (1999) detected, at Boca do Rio, an atypical sedimentary unit, believed to have been deposited by the tsunami associated with the 1755 Lisbon earthquake. Furthermore, accurate historical descriptions of episodes of marine flooding in Boca do Rio existed (e.g. Silva Lopes, 1841; Pereira de Sousa, 1919). The unit detected marked "a distinct sedimentological and micropalaeontological break from the deposits enclosing it. Detailed textural analysis through vertical sections of these sub-units shows abrupt changes in particle size characteristics. The lowermost section of the deposit appears to have been deposited from a highly turbulent water mass, which was able to transport gravel, sized clasts as well as gravel sized mud balls eroded from underlying material. The water mass rapidly lost energy, leading to the deposition of predominantly sand, silt and clay particles. Sharp breaks in textural characteristics are likely to be due to changes in current direction caused by wave reflection or swash-backwash interference. The main sources of sand sized material within the deposit are the seaward barrier (beach-fore dune system). The tsunami deposits (Boca do Rio) shares many of the sedimentary characteristics of tsunami deposits from other sites around the world" (Figure 4.6).

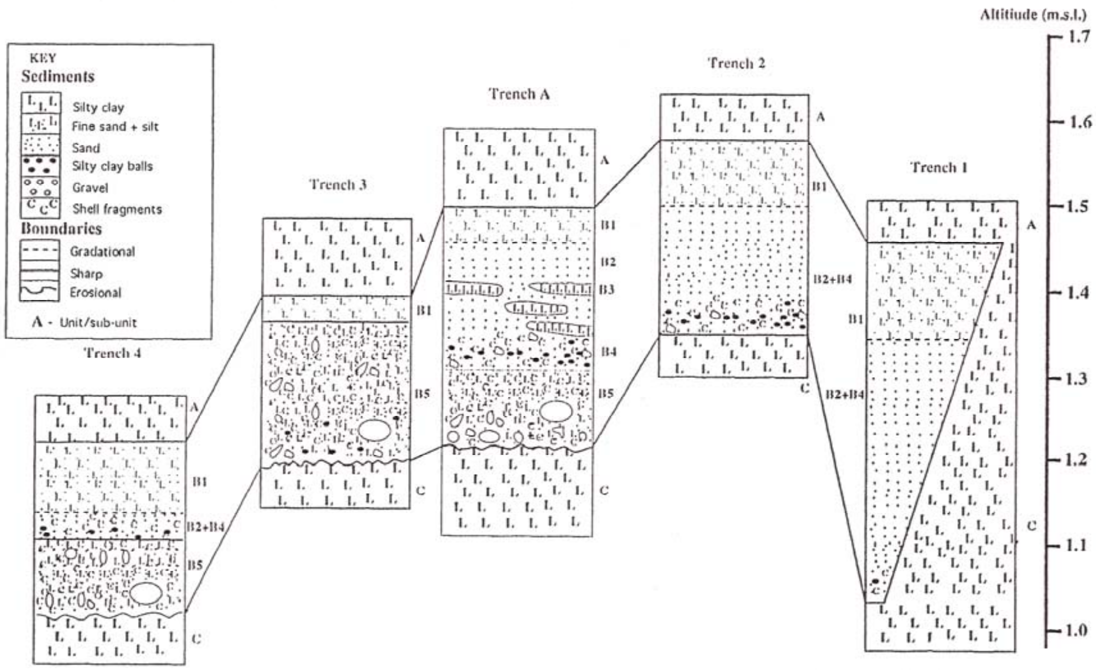

Figure 4.6- Variation in sedimentary characteristics of the tsunamigenic unit (Unit B) within trenches in the main valley at Boca do Rio (Hindson & Andrade, 1999)

According to Hindson & Andrade (1999) the tsunamic deposit at Boca do Rio is sedimentologically complex; five sub-units were identified. The tsunamic sub-unit referred by Dawson et al. (1995) as the "chaotic layer" "consists of a massive structureless matrix of detrital sediment ranging from a muddy/sandy conglomerate to coarse muddy sand. The coarser fraction is poorly sorted and shell fragments are also quite abundant. The lower contact is erosional and its upper contact highly irregular." (Hindson & Andrade, 1999). Moreover, it was mentioned that the unit fines inland; the proportions of different sizes of sand vary greatly through the event unit. Granulometric studies confirmed the complexity of the tsunamic unit. Thermoluminescence and optically stimulated luminescence dates were obtained, indicating that the tsunamic unit was contemporary of the AD 1755 Tsunami.

A sedimentary deposit attributed to the AD 1755 tsunami was also recognised by Kortekaas (2002) in Martinhal, western Algarve. Detailed description of the results and comments are made in Chapter 7.

Luque et al. (1999) related the sedimentary sequence of the Valdelagrana (Cadiz, south western Spain) washover deposits to the three consecutive waves that breached the sand ridge, flooding the marshes inland. Geomorphology, historical documents, sedimentology and grain size was studied in the washover fans. The dates obtained for the deposit were within an interval that included the AD 1755 Tsunami. Comparisons were established, by the authors, with previous deposits of the AD 1755 Tsunami (e.g. Boca do Rio).

Scheffers & Kelletat (2005) discovered in the Cabo da Roca-Cascais area (west of Lisbon) several relics of tsunami in the form of single large boulders, boulder ridges, pebbles and shells high above the modern storm level. Dates obtained using radiocarbon and Electron Spin Resonance (ESR) pointed not only to the AD 1755 tsunami but to other (older) tsunami events.

4.4- Storm processes along the Portuguese coast

Although frequently subject to storm events there are no published papers that focused on the sedimentological signature of such events in the Portuguese coast. However, there are some historical accounts in the most populated coastal areas. Furthermore, those reports are many times inaccurate and only refer the anomalous wave activity and the damage caused in infrastructures. Since the XIX century local journals have gathered information about the local effects of the major storms that affected the coast of Portugal. More recently, cycles of coastal flooding are trying to be established however without success so far.

4.5- Conclusion

The destructive effects of tsunamis have been felt is many coastal areas of the world. A review of the most important tsunamis that occurred in the Iberian Peninsula in the last 2500 years is presented. Although an area not subject to regular tsunamis, the Iberian Peninsula has been affected by approximately 50 tsunamis in that time.

Results to date show that the 1755 tsunami has left a deposit in distal sediments that is difficult to distinguish from sediment lay down by more normal energy storms. The problem of recognising the extent of ancient tsunamis has clear implications for the modelling and prediction of the effect of a tsunami on any particular section of coastline, because it depends on wave strength, coastal form and aspect, and available sediment sources.

In Europe the most destructive tsunami in historical times was the 1775 Lisbon tsunami. For most coastal regions of Portugal, the destructive effects of the 1755 tsunami were more disastrous than the direct effects of the earthquake. According to historical accounts the first three waves of the tsunami were particularly destructive along the west and south coasts of Portugal. The events on the morning of the 1st of November of 1755, All Saints Day, in Lisbon, Portugal, forced major and lasting changes in society, religion, philosophy and science all over the World.

It is, however, important to increase the knowledge on the effects of the tsunami on the shores of Portugal to have a broader picture of the causes, the behaviour, the environmental consequences and the vast devastation caused by the 1755 tsunami.

5. Methodology

5.1- Introduction

Palaeoenvironmental and palaeotsunami research requires a wide range of proxies and procedures to obtain results that verify characteristics of the deposits associated with the marine origin and high energy of events such as storm and tsunami. The techniques presented in this chapter were used to examine sedimentary evidences left by major abrupt marine invasions in the study areas. The proxies include analyse of historical record, coring, stratigraphic description, magnetic susceptibility analysis, x-ray and digital photography, geochemical analysis (e.g. Atomic Absorption Spectrophotometry, X-Ray Fluorescence, *loss-on-ignition*, grain size analysis, palaeontological analysis and dating methods (Optically Stimulated Luminescence and ^{210}Pb) (Figure 5.1).

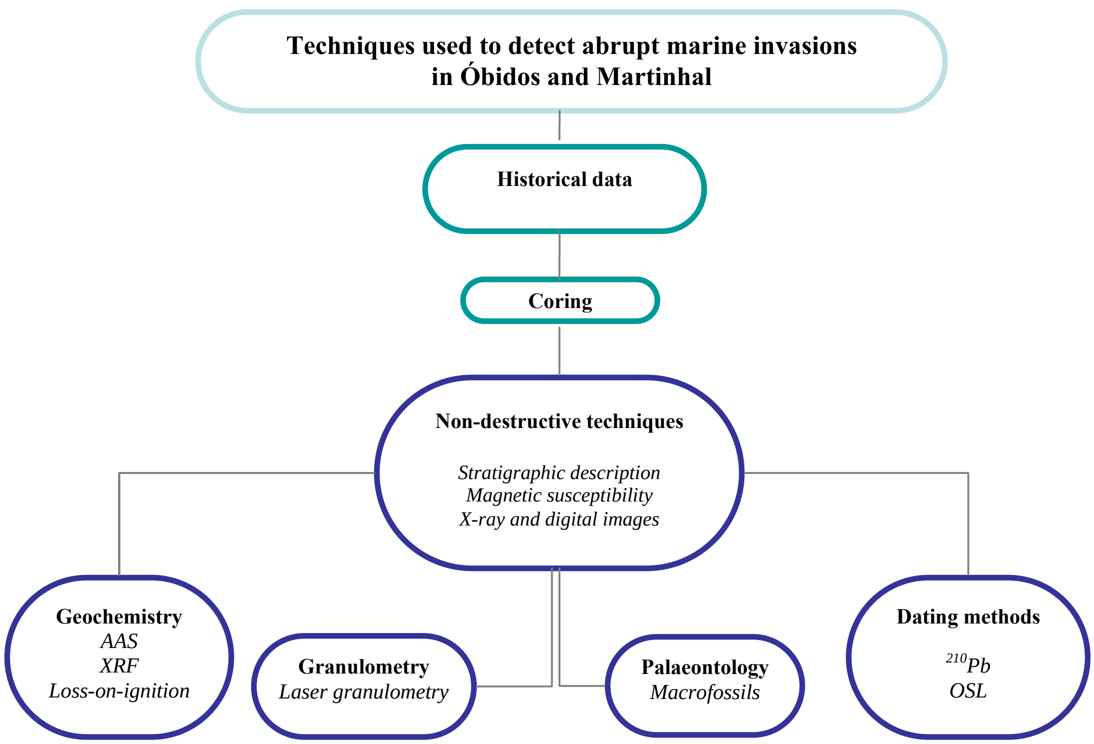

Figure 5.1- Organizational chart of field and laboratory techniques used.

5.2- Historical record

The use of historical data is crucial to understand the effects and origin of major catastrophic events (e.g. earthquakes, tsunamis, major storms, etc.). Although of limited use in terms of geological time, historical records are an indispensable tool for palaeotsunami research. Records of major storms and tsunamis over recent times can be found almost everywhere in the World (see chapters 2, 3 and 4). Furthermore, historical data is extremely useful to establish patterns of coastal flooding. On the other hand the geological record is a decisive proxy to complete any inaccurate or non-existent historical record. Historical record and geological record can complement each other.

However, historical descriptions are not always accurate and tend to exaggerate consequences and other important aspects. One example is the death toll of the AD 1755 Lisbon earthquake. Documents can be found referring numbers that vary from 30000 to 90000 dead. Careful must be taken when analysing historical documents. Nevertheless, historical documents can provide useful and some times crucial information.

The research to historical documents was conducted primarily with the purpose of detecting areas that had been strongly affected by the AD 1755 tsunami (through extensive and detailed references in the literature) and secondly to collect descriptions of the effects on selected areas. This was followed by a selection of potential locations to study, that required a combination of accurate historical record with potential geological\sedimentological interest. The collection of geological information followed. Moreover, maps (topographic, bathymetric, and geological) were obtained; a wide range of geological data was collected and extensive scientific literature was gathered.

The historical data and geological information was collected from the National Archive of Torre do Tombo, in Lisbon, the City Museum of Lisbon, from City Council libraries (e.g. Óbidos, Caldas da Rainha, Mira, Aveiro, Ílhavo, Cantanhede, Figueira da Foz, Coimbra, Nazaré), from governmental agencies (Ministério da Agricultura, Instituto da Água, Direcção Geral das Florestas, Protecção Civil), from University libraries (University of Coimbra and

University of Lisbon) and from different marine authorities (Porto da Figueira da Foz and Porto de Peniche).

The selection of the study areas was completed after a long process of collection of information and analyse of documents and maps.

In conclusion, historical record provides the foundations for any palaeoenvironmental research. Furthermore, a partnership between geological data and historical documents is crucial to any palaeoenvironmental study.

5.3- Coring

The acquisition of complete and undisturbed sediment cores was fundamental for the research conducted. The locations selected were coastal lagoons, due to their depositional conditions and susceptibility to abrupt marine invasions. It is commonly accepted that lake sediments can provide complete stratigraphic sequences for palaeoclimatic interpretation. “Lake sediments serve as a natural archive repository for environmental changes occurring in its drainage basin and outside of it” (Leroy, 1998). The corer widely used for this type of sedimentary environments is the square-rod piston corer.

The corer used in Óbidos was the Livingstone piston corer, later modified by insertion of an internal square rod (Figure 5.2a). The Livingstone corer can collect cores in 1 m long sections from lakes as much as 30 m deep Wright (1991). Lagoa de Óbidos is a shallow lagoon. The Livingstone corer can be operated from a boat, a raft or from a pontoon. In the case of Lagoa de Óbidos, the acquisition of cores was made from the side of the boat (Zodiac) after stabilising the boat in each station with the use of two anchors (Figure 5.2b). Water depth was measured before collecting the samples. The procedure described by Wright (1991), was followed; e.g. “The rubber piston should be adjusted to tightness (when the tube is wet). (…). The corer is lowered to the starting depth, and the piston wire is drawn as tight as possible and firmly secured (…). When the wire is set the internal square rod is then lifted one m by the connecting rods and cocked with a quarter turn. (…) For the drive that follows the drivers should place their hands at various levels of the rod so that the push can steady for a full meter".

Immediately after collection of the core, each section was extruded to PVC pipes (55 mm of diameter). The sections were measured to detect if any loss of sediment had happened and to correct depths accordingly. No sediment compaction or deformation was detected in any core. The cores were then wrapped in plastic film, the pipes labelled and stored. In Óbidos a transect perpendicular to the coast (e.g. NNW – SSE) was followed. Occasionally alternated holes were used to certify the stratigraphic sequence was uninterrupted (overlapping sections). Following fieldwork the cores were stored in a cold room at 4 ºC and later opened for a wide range of laboratory techniques.

The Martinhal cores were collected by Dr Stella Kortekaas (1997). According to Kortekaas (2002), in Martinhal "an Eijkelkamp hand gouge auger with a 3 cm diameter chamber was used to study the stratigraphy (…) and a 10 cm gouge auger was used to take samples. (…) In order to recover sand under the water table a Van der Staay suction corer was used (…). This coring system consists of two plastic tubes that fit into each other. The inner tube works as a piston and has a piece of leather at its end, which fits air-tight into the outer tube, producing a vacuum. When the outer tube is pushed into the sediment, the piston is pulled up and the core chamber is filled with sand. (…). A core catcher at the end of the outer tube also prevents the sediment from falling out".

Studies of recent environmental changes from lacustrine or marine deposits undoubtedly require high-resolution sampling of the sedimentary record. To obtain a complete and undisturbed stratigraphic sequence is a requirement for any palaeotsunami research.

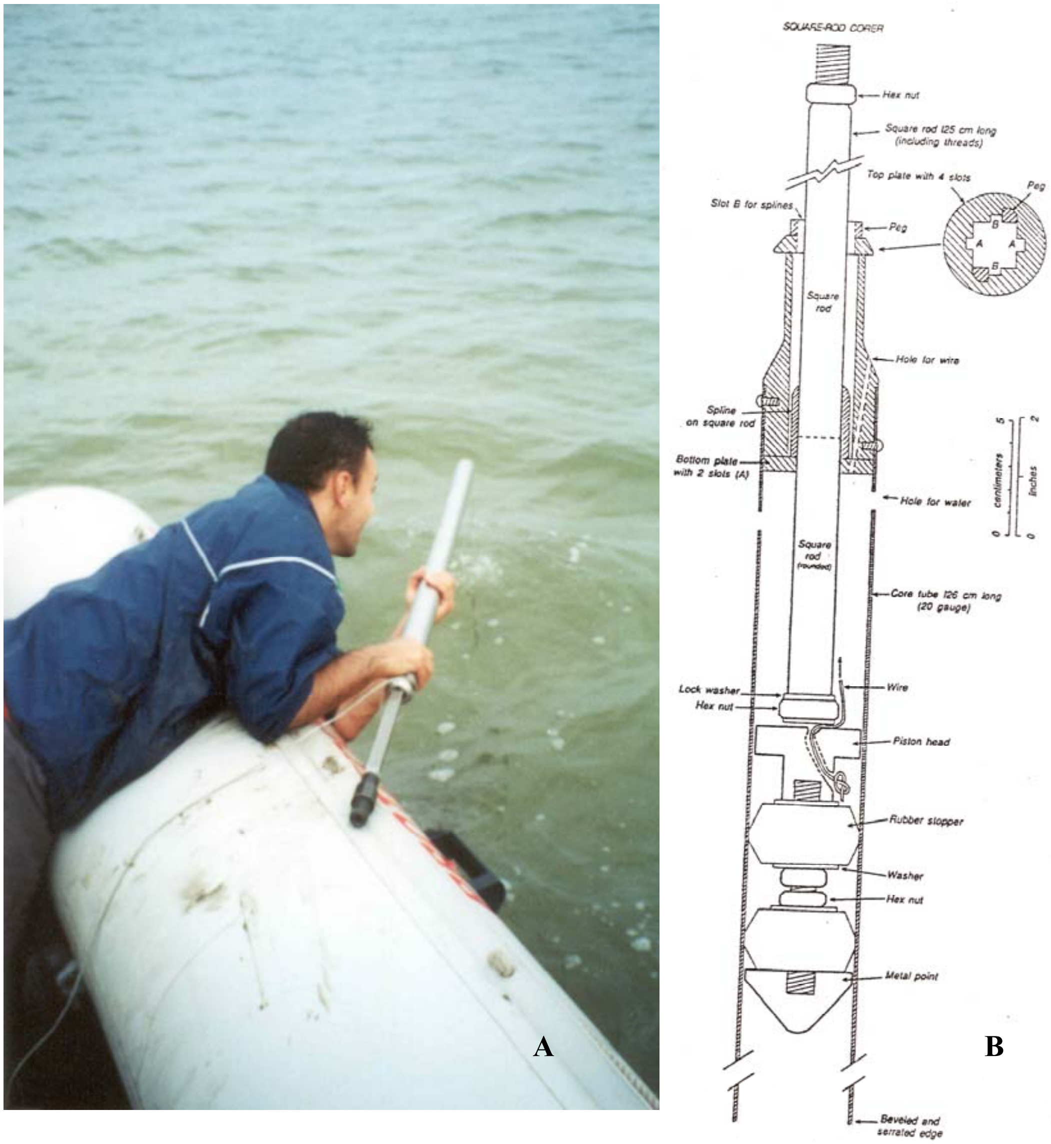

Figure 5.2- Livingstone corer

Figure 5.2a - Livingstone corer being washed from the side of a boat. (Photo of Eduardo Costa, 2002)

Figure 5.2b- Schematic representation of the Livingstone corer (Wright, 1991)

5.4- Stratigraphic description

The standard core description was conducted according with the ODP (Ocean Drilling Program) visual core description form. The detailed description included granulometry, macroscopic sedimentary structures, the nature of contact between different stratigraphical units and colour (according to the Munsell chart). Moreover, "In the routine description of a section, first defines bedding on the basis of variations in sediment lithology, colour, sedimentary structures, or other pertinent characteristics, and then proceeds to describe the four major characteristics of each bed: thickness and attitude; sedimentary structures and bedding planes; lithology and colour; degree of disturbance by the drilling process" (Mazzullo et al., 1988).

All the cores from Óbidos were described immediatelly after the magnetic susceptibility analysis and subsequent opening of the sections (presented on Chapter 6). The cores from Martinhal were described previously to any analysis.

5.5- X-ray and digital photography

Digital photographs were taken on every core studied. The purpose was to have a permanent record of the stratigraphy of the cores. The photos were taken using a Sony Cyber-shot digital camera (4.1 Mega pixels).

X-ray radiography of sediment cores is a fast, non-destructive scanning and recording technique, which simplifies the determination of sedimentary properties. X-ray photographs were made at selected intervals to reveal sedimentary structures. X-rays were used to highlight features not visible by visual description. The x-rays photographs were obtained at the Hillingdon Hospital. The x-rays were digitised using a Kodak LS40 Film digitizer. Schematic drawings revealing the most important features were made and are presented on Chapters 6 and 7.

5.6- Magnetic susceptibility

Magnetic susceptibility is the capability of attraction of minerals to a magnet. There are five types of magnetic behaviours: ferromagnetic (e.g. Iron), ferrimagnetic (e.g. Magnetite), canted antiferromagnetic (e.g. Hematite), paramagnetic (e.g. Biotite) and diamagnetic (Organic matter, Water) (Sandgren & Snowball, 2001). The majority of substances have elements with different types of magnetic susceptibility. Sediment deposits are also generally composed of a variety of different material with different magnetic characteristics.

Magnetic susceptibility measurements on the unopened cores were conducted using a Bartington MS2C magnetometer. MS2C (Figure 5.3) is a sensor that creates a magnetic field from an alternative current and measure the material magnetisation. MS2C is a device used to measure the magnetic susceptibility of cores. Every core was analysed every 2 cm. The top and bottom cm of each core were excluded because the sensor measured both air and the core. The data was transferred immediately from the sensor to Multisus 2, a software program that allows measurements on single samples and whole cores to be recorded and stored on file. "The software is able to compensate for: equipment drift, container susceptibility and core diameter." (In Operation Manual Multisus 2 for Windows, 1999). The results were then plotted and different stations were then co-related. Magnetic susceptibility measurements are non-destructive, easy to perform, with results often representative for the bulk composition of the investigated sediments.

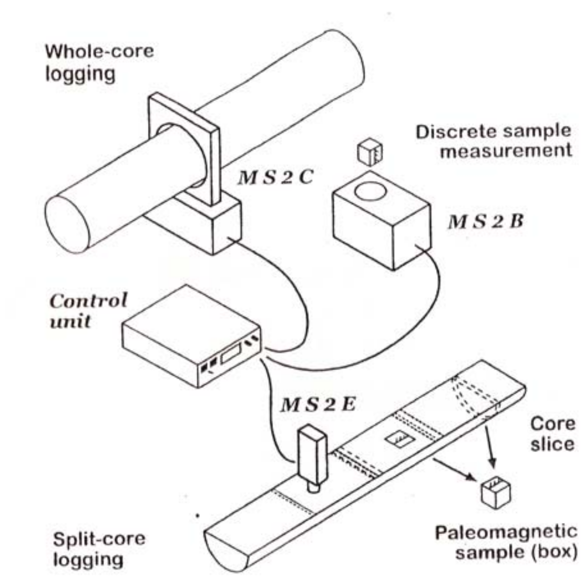

Figure 5.3- Different types of Magnetic susceptibility sensors from Bartington (Nowaczyk, 2001)

5.7- Geochemichal analysis

A study by Fairnburn, in 1951, shed serious doubts on the reliability of geological chemical data (Van Loon, 1980). Furthermore, that paper emphasizes the importance of proper sampling and preparation to obtain accurate results. More recently, with the development of a wide range of instruments, the geochemical analysis has proven to be undoubtedly useful (see Chapter 3). It can be an important auxiliary when conducting sedimentological research.

5.7.1- Loss on Ignition

This technique is used to determine the amount of organic matter and carbonates (two different temperatures) (Bengtsson & Enell 1986)."
Moreover, "The determination of organic carbon content is of considerable importance in palaeolimnology where it provides an index of biological productivity in former lake basins" (Lowe et al., 1997). The organic matter present in the sediments of one lake is originated mainly from plants (around 90%) that lived in the lake waters and from animals (around 10%).

Loss-on-Ignition has been measured, at the Department of Geography and Earth Sciences, in every core from Óbidos and on core 27 from Martinhal. Water contents are not an absolute value because they have been obtained some time after coring. It may however provide us with trends. Loss-on-ignition has been made on 105 ºC during 12 hours for the loss of water; on 550° C during 2 hours for the loss in organic matter; and on 925 °C during 24h for the loss of carbonates. The results were then inserted in an excel worksheet and charts were plotted. The sum used for the % is the sum of organic matter and carbonate residue (water is not included).

This method provides us with a rapid first estimate of the composition of the sediment. Furthermore, it was important when correlating different samples.

5.7.2- Atomic Absorption Spectrometry

The geochemistry of the sediments was analysed, at the Department of Geography and Earth Sciences, Brunel University, to detect changes in the following elements: Al, Ca, Fe, K, Mg, Mn, Na, Pb, Zn. Flame Atomic

Absorption Spectroscopy with a Thermo Jarrell Ash S11 and a Perkin-Elmer Model 2380 Spectrophotometer measured the elements.

All the cores from Óbidos and Martinhal were sub-sampled every 2 cm. The samples were then submitted to a long treatment process. Initially the samples were grinded and weighted. All glassware used was pre-cleaned with 10 % Hydrochloric Acid. *Aqua regia* (3:1 concentrated Hydrochloric Acid: concentrated Nitric Acid) was slowly added and the sample was warmed on a hot plate. After 2 to 4 hours the sample was then decanted and to the residue was added 50% Hydrochloric Acid. This was followed by a new period on the hot plate (approximately 4 hours). Finally the sample was removed from the hot plate, filtered using acid rinse glassware and filter papers. The remaining liquid (100% concentration) was use to produce diluted samples (10% and 1% concentration) and analysed in the spectrometer. A number of standards (usually 3 to 5) in increased concentrations, as well as a blank, were used to cover the concentration range. The standards were run in absorbance to check the linearity of the calibration curve. The correlation coefficient of the calibration line was always 0.98 or higher. Each sample was read three or four times and the result presented was the average of those values. The results accepted had always a variation of less than 10% between the 4 readings of each sample analysed. The calibration was checked once every 10 or12 samples. The results were then plotted in to excel charts.

5.7.3- X-ray fluorescence (XRF)

This is a standard technique for determining the chemical composition of rocks. XRF is a technique for elemental analysis, involving the measurement of secondary X-rays emitted by a target bombarded with high-energy x-rays. For each element, the intensity of its characteristic radiation is proportional to the amount of the element in the specimen. The radiation emitted is measured and compared with that emitted by standards of known composition, to identify elements present. This analyse was only conducted on the core Mart 27 from Martinhal. X-ray fluorescence analysis was conducted at the ERC (Environmental Research Centre, Brunel University). The samples were grinded and approximately 4 grams were analysed. The charts obtained were scanned and are presented on Chapter 7.

5.8- Grain size analysis

Grain size analysis was conducted using a Malvern 2000 Series Laser Granulometer on samples from all cores. Statistical grain size parameters, e.g. standard deviation, skewness and kurtosis, were calculated, using formulas based on MacManus (1988).

Initially the sub-samples were measured in terms of volume and weight. Secondly, samples were treated with 1.5% Calgon (Sodium Hexamataphosphate). That was followed by the sieving of the samples using a 1 millimetre sieve. The residue was weighted, collected and stored in 50 millimetres plastic tubes properly labelled. Finally the samples were analysed in the granulometer. The results obtain were exported to Excel files and charts were plotted.

5.9- Palaeontology

Fossils present in the stratigraphic unit are undoubtedly an important resource to detect abrupt events such as tsunami and storms. With that frame of mind palaeontological analysis (macrofossils) were analysed in the Óbidos cores.

The totality of cores from Óbidos was sub-sampled for macrofossils analysis every 2 cm. The sediments were treated with 1.5% Calgon (Sodium Hexamataphosphate) or with 1% Sodium Pyrophosphate. Samples were sieved using 500, 125 and 63 μm sieves. However only the samples affected by the main event unit (see Chapter 6) were studied and macrofossils counted using a magnifying glass with a routine magnification of 10x 25x). The palaeontological analysis of the Martinhal samples was conducted by S. Kortekaas (2002). The Martinhal samples were subject to foraminifera studies (conducted by S. Kortekaas) while the Lagoa de Óbidos samples were subject to macrofossils analysis. Both analyses were used to demonstrate increases in marine species or express the high energy of the events.

5.10- Dating methods

As referred on chapter 3, dating tsunami deposits is complicated. The methods selected for this research were that recommended by literature for this type of events.

The dates of the deposits from Óbidos and from Martinhal have been obtained using 2 dating techniques (e.g. Optically Stimulated Luminescence (OSL) and ^{210}Pb).

5.10.1- Optically Stimulated Luminescence (OSL)

"Optically Stimulated Luminescence is a dating technique of particular use when sediments had limited exposure to light before burial" (Aitken, 1992). "This technique measures the luminescence emitted from the most light-sensitive electron traps in particular minerals, especially quartz and feldspars, following exposure to light" (Huntley et al., 1996). Optical stimulation is provided by using a green light source (or green laser) or, in the case of feldspars, an infrared light source (Hütt et al., 1988; Wintle et al., 1994). Recently this technique has been applied in several palaeotsunami studies (see Chapter 3).

The event unit (see Chapter 6) from Óbidos was dated with OSL at the Geochronology Laboratories, University of Gloucestershire.

The sediment was extracted from the extruded section (Ob 1.2) under controlled laboratory lighting conditions provided by Encapsulite RB-10 filters. A 10 cm long segment (event unit) of the core was separated. Two millimetres of sediment was removed from each vertical face to isolate that material potentially exposed to light during core extrusion. The remaining "bulk" content of the sample was dried at 40 ºC for 48 hours and then dry sieved. Quartz within fine sand (125-180 microns) fraction was isolated. This grain fraction was treated with 10% hydrochloric acid and 10% hydrogen peroxide to attain removal of carbonate and organic components. The sample was then etched for 60 minutes in 40% hydrofluoric acid, in order to remove the outer 10-15 micron layer affected by alpha radiation and degrade the sample's feldspar content. Whilst in hydrofluoric acid, the sample was continuously stirred using a magnetic stirrer and follower apparatus in an attempt to achieve isotropic grains. 10% hydrochloric acid was added to remove acid soluble fluorides. The sample was dried, re-sieved and quartz isolated from the remaining heavy mineral fraction using a sodium polytungstate density separation at 2.68g.cm^{-3}. 24~6 milligrams aliquots of quartz from the sample were then mounted on aluminium discs for the determination of equivalent dose values. Quartz was used as the minerogenic dosimeter primarily because of the stability of its datable signal over the Quaternary period in contrast to the anomalous fading of comparable signals observed for other ubiquitous sedimentary minerals such as feldspar and zircon (Wintle, 1973; Templer, 1985).

Luminescence measurements were made using an automated TL-DA-15 Risǿ set (Markey et al., 1997). Equivalent Dose (D_e) values were obtained through calibrating the "natural" optical signal, acquired during burial, against "regenerated" optical signals obtained by administering known amounts of laboratory dose. Specifically, D_e estimates were obtained using a Single-Aliquot Regenerative-dose (SAR) protocol, similar to that proposed by Murray & Wintle (2000).

In-situ measurements of gamma dose contributions were perfomed by Becquerel Laboratories, Australia, on material sub-sampled from the "bulk" sample to determine the average gamma and beta dose contributions. Dose rate calculations, following those described by Aitken (1985), incorporated beta-attenuation factors (Mejdahl, 1979), dose rate conversion factors (Adamiec & Aitken, 1998) and the absorption coefficient of present water content (Zimmerman, 1971), with a 25% relative uncertainty attached to reflect potential temporal variations in past moisture content. Estimations of cosmic dose followed the calculations of Prescott & Hutton (1994).

The luminescence age was obtained by dividing D_e value by the mean total dose rate value. The error on luminescence age represents the combined systematic and experimental error associated with both D_e and dose rate values.

5.10.2- ^{210}Pb

There are several dating methods for the most recent Holocene. However the more exact method is ^{210}Pb, for studies involving the last 150 years. ^{210}Pb dating establishes the sedimentation rate for the top of the stratigraphic column, allowing an approximated date for units within the column.

Lead has a half-life of 22 years and has a great dispersion in Nature. Lead (Pb) is regarded as an element that is very efficiently scavenged by most natural solids (e.g. oxides, sulphides, organic matter, and clay materials), and subsequently exhibits little tendency to be remobilized. These characteristics are indeed fundamental to the widely used ^{210}Pb dating method for aquatic sediments. The dating method itself involves several chemistry treatments and a complex network of processes. From Lagoa de Óbidos only Core Ob 1.1 was used for ^{210}Pb dating.

The core was sub-sampled every cm on the top 30 cm of section 1. Furthermore the following 40 cm (31 to 70 cm) of the section were sub-sampled every 5 cm. The samples were dried at 60 ºC and grinded to less than 1 millimetre particle size. Radioactive spike (^{209}Po) was added and the weight was measured the minute the spike was added. 30mls of *aqua-regia* (50%HCl+HNO3, ratio 3:1) was added and the solution was warmed for 4hours. An extra 15mls of aqua regia were added and the solution was warmed for another 4hours. The sample was then filtered and warmed until full evaporation took place. 5.5mls of 50%HCL was added to the dried residue. De-ionised water was added to produce 0.8M for acid concentration. 15grs of ascorbic acid powder were added. The silver discs were then placed on the 50ml beaker and gently warmed for 36h. The silver discs were then dried for 24hours and counted using the alpha spectrometer. The samples were then analysed in a Ortec Alpha Spectrometer at the Department of Geography and Earth Sciences, Brunel University. The results obtained were then calculated based in the Constant Rate Supply method

5.11- Conclusion

A complete palaeoenvironmental study requires a vast range of techniques and resources. The results of the majority of the techniques cannot be considered *per se* but each analyse can provide important information and complement other data produced by other proxies. As most tsunami sedimentary characteristics are ambiguous (see Chapter 3) only an approach that applies several techniques can be successful. Also local aspects should be taken in consideration as tsunami and storm deposits are strongly affected by local conditions.

6. Óbidos

6.1- Introduction

Lagoa de Óbidos, located in the western coast of Portugal, between Cabo Carvoeiro and S. Martinho do Porto (Figure 6.1), is a lagoonal system with an NW-SE orientation. The lagoon is positioned in a shallow depression, of irregular and unstable contours due to the sedimentological and hydrological dynamics of the region. Lagoa de Óbidos, as many coastal lagoons, is a transitional system located under the influence of both marine and fresh waters. The balance between marine and fresh water influences controls the geochemical, biological and sedimentological cycles in the lagoon. Coastal lagoons tend to evolve to swamps and ultimately to disappear, Lagoa de Óbidos is no exception. The present-day lagoon is what remains from a vast lagoonal system that once reached the Walls of the historic village of Óbidos.

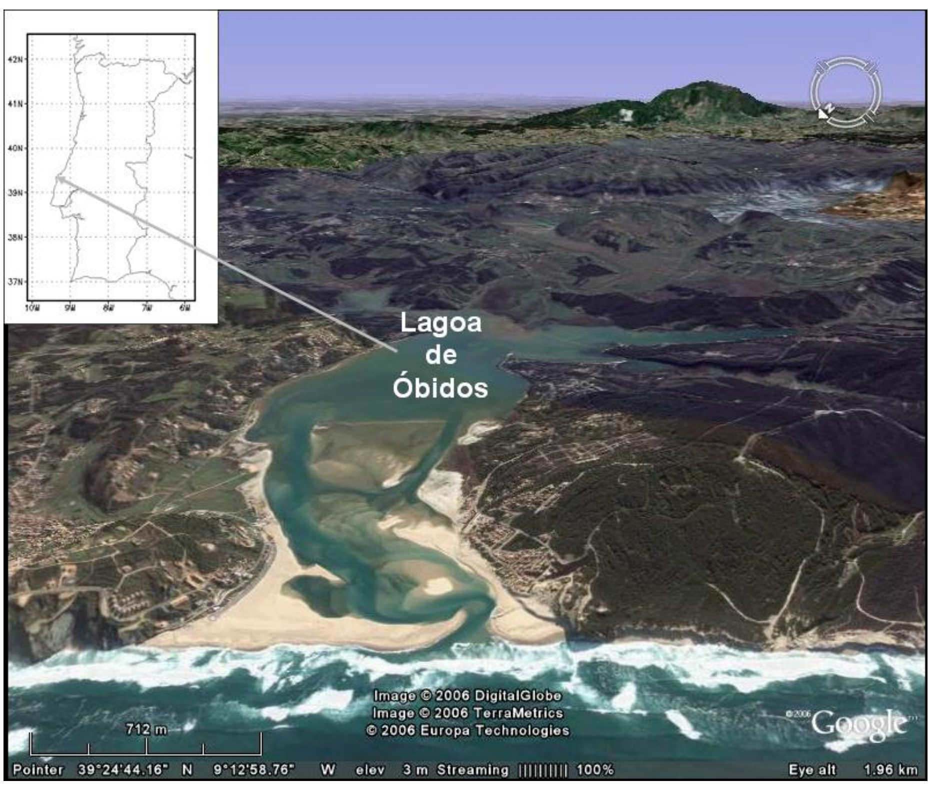

Figure 6.1- Lagoa de Óbidos (Perpendicular view-aerial image from GoogleEarth)

Lagoa de Óbidos is one of the largest coastal lagoons in Portugal. This lagoon was an estuary but due to sedimentary accumulation, especially after the Little Ice Age, became a lagoon with a small channel, the Aberta (Figure 6.2), to communicate with the Atlantic Ocean. The Aberta is located between the Facho Hill and the Gronho Rock (both abrupt cliffs that reach more than 10 metres above sea level). Lagoa de Óbidos is extremely shallow, its deepest part is located in the centre of the lagoon and is approximately 250 cm deep. The present-day lagoon can be sub-divided in 2 major areas; one closest to the Aberta, marine dominated and another area, to the east of the small overwash fan, marking the landward limit of normal storm surges in the area, where the marine influence is smaller and the polluted rivers (Real River, Arnóia River and Cal River) are the main sedimentary contributors (Figure 6.3 and 6.4). The sand barrier (Aberta) has 1500 m long and is extremely robust.

According to Dinis et al. (2006), Óbidos, S. Martinho do Porto and Pederneira (Figure 6.6) are relicts of vast lagoonal systems formed in the diapiric basin of Caldas da Rainha following its drowning by the Holocene transgression; the establishment of detrital barriers (Óbidos and Pederneira), determined by the deceleration of the sea-level rise rate in the Middle Holocene and the existing narrow inlets in rocky basement (Pederneira and S. Martinho do Porto) provided sheltering to these lagoons which intensively silted up, especially after the Christian Re-conquest (end of the 12th century).

The transgression period was also responsible for the reorganization of the fluvial dynamic. Lagoa de Óbidos progressively reduced both the water depth and wet surface following an evolutionary pattern similar to other small Portuguese coastal lagoons (e.g. Dinis et al, 2006; Freitas, 1989a, 1989b; Freitas & Andrade, 1998; Bao et al., 1999; Freitas et al., 2002a, 2002b).

The history of the region is clearly marked by the lagoon. Romans conquered the village of Óbidos using the lagoon, that at the time reached the Óbidos village Walls. Apparently, around AD 700 the lagoon stretched to Santa Rufina; were the Goths built 2 churches and made references to the proximity of the lagoon. From the XVI century onwards there are several references (e.g. maps and historical documents) acknowledging the fact that it was vital to keep the Aberta opened and also demonstrating that the lagoonal area was decreasing dramatically. The first reference to Lagoa de Óbidos as a lagoon instead of an estuary is from AD 1736 and AD 1751 (Freitas, 1989a). Periodically the population was summoned by royal decree to help in the re-opening of the Aberta. More recently (since 1950s), the intervention in the Aberta has become increasingly regular. However, the majority of the central and eastern areas of Lagoa de Óbidos have not been dragged.

Due to the presence of the Aberta the lagoon has a strong capacity to retain the fluvial sediments. In contrast, the coastal area of the lagoon is strongly affected by littoral drift and by wave erosion. The input of sediments in the lagoon (except the Aberta) is clearly fluvial dominated.

Lagoa de Óbidos is located in a fault or the boundary between the cemented Upper Jurassic sandstones and the more loose Lower Cretaceous clasts. The continental platform is narrow and has two important characteristics that invert the littoral transport and the littoral drift (form N-S to S-N): the submarine Nazaré Canyon, that reaches 500 m deep just a few hundred m from the Nazaré beach, and the Peniche tombolo (Figure 6.6).

According to Shepard (1963) the coastline around Lagoa de Óbidos is essentially Primary, (e.g. the Atlantic Ocean assembles against a landform essentially shaped by tectonic action). Secondary reworking by marine agents shaped a detached beach-dune system between Nazaré and Salgados and cut scarped cliffs further south (Figure 6.6). According to Dinis et al. (2006) the continuity of the coastline is interrupted by the outlet of the Alcoa stream (at present stabilized by the Nazaré harbor) and the lagoons of São Martinho do Porto and Óbidos (Figure 6.6).

This high energy, swell-dominated stretch of coast is fully exposed to far-generated waves in the Atlantic. The yearly mean significant wave height and peak period off shore the northwestern coast are of 2-2.5 m and 9-11 s and the modal height and period range between 1.5-3 m and 9-14 s; this wave regime corresponds with WNW to NNW swell generated in high latitudes in the North Atlantic, and prevails more than ¾ of the year (Carvalho & Barceló 1966; Costa 1994). The shore wave regime is somewhat reduced in height due to early breaking (cf. Carvalho & Barceló, 1966) wave height being of approximately 2 m in the study area.

The lagoon appears to be responsible for the decrease of littoral drift because it works as a sedimentological reservoir receiving sand from the near-by beaches. However, the intertidal sand banks only stretch to 1/3 of the lagoon (overwash fan) the remaining area of the lagoon is not affected by the geodynamic of the coastal area.

The lagoon with an approximate area of 7 km^2 is in a slow natural process of infilling that has been resist by the effort of humans.

Figure 6.2- The Aberta of Lagoa de Óbidos (Photo Jorge Dinis, 2003)

Figure 6.3- Photo from approximately the centre of Lagoa de Óbidos (Station 4) view towards the sea. (Photo Eduardo Costa, 2002)

Figure 6.4- South-eastern part of Lagoa de Óbidos
(aerial photography, Serviços Nacionais de Informação Geográfica, 2002)

6.2- Previous studies

Lagoa de Óbidos social, economic and cultural importance has motivated interest from the scientific community. The vast majority of papers published are based in historical documents and in the historical evolution of the lagoon.

For instance, Freitas (1989a) published a paper regarding the evolution of Lagoa de Óbidos in historical times. The author used historical maps (Figure 6.5) and by overlapping the maps established the evolution of the limits of the lagoon, the evolution of the position of the Aberta and predicted the erosion and sedimentation rates, based in the decrease of the lagoonal area. Furthermore, Freitas (1989a) also compare maps from 1917 and 1980 concluding that the total sedimentation for those 63 years was 2700000 m^3 and the total erosion for the same period was 250500 m^3. The author established an erosional rate of 6mm per year and a sedimentation rate of 12 mm per year.

Recently (since the 1950s) engineering studies have been conducted (specifically in the Aberta zone) in search of a solution for the historical cyclic closure of the channel of communication with the sea. Due to the ecological importance of Lagoa de Óbidos several papers have been published concerning the flora and fauna of the lagoon and surrounding area.

The stratigraphy of the lagoonal sediments has not been studied so far. The sedimentological studies in the lagoon focused in the surface sediments of the lagoon (e.g. Godinho et al, 1984; Freitas, 1989b). Godinho et al. (1984) conducted 29 chemical analyses on the surface sediments of the lagoon. The authors concluded that Lagoa de Óbidos is an extremely sensitive geochemical environment. Moreover, the influences of marine and fluvial influxes of water and sediments were detected. The fluvial influence was more obvious in the clayish fraction and in the samples from the interior of the lagoon while the marine influence was more noticeable in the sandy fraction and in the coastal samples of the lagoon. Furthermore, the human influence was noted in the higher concentration levels of some specific elements (e.g. Pb, Hg, Zn, Ba). The values were attributed to the industrial area of Caldas da Rainha. The landward limit of the tides was also detected by clear changes in the geochemical content (e.g. Si, Ca, Na, etc), as well as changes in the sedimentological content.

Freitas (1989b) collected 52 samples in the surface of Lagoa de Óbidos, using a Hydro-Bios-Kiel corer. The deepest sample had 50 cm long. Unfortunately no stratigraphic description was conducted. The samples were submitted to grain size analysis and mineralogical analysis. The author concluded that the sedimentological marine contribution to the lagoon is restricted to the Aberta. Moreover, it was clear that in the interior of the lagoon the clayish fraction dominated and that the samples presented a more diverse mineralogical content, indicating a higher fluvial influence. The author concluded that the lagoonal system has two major sedimentological units: one, close to the Aberta, where sand dominates; other, in the interior of the lagoon, where clay dominates. In addition, Freitas (1989b) detected the presence of quartz in the samples collected in the Aberta; muscovite (exclusively in the right margin of the lagoon) and biotite in the small overwash fan; zircon, tourmaline and andalusite in the centre of the lagoon; and clay minerals (caulinite and ilite) in the interior of the lagoon. The author also detected that the biogenic fraction is mainly composed by shells and shell fragments (molluscs and gastropods). However, the biogenic fraction decreases in the interior of the lagoon. Furthermore calcareous Nannoplancton was detected in the eastern areas of the lagoon. The organic content is low in the Aberta area and particularly high in the centre and the interior of Lagoa de Óbidos.

The sedimentological research in Lagoa de Óbidos has so far focused in the granulometric, mineralogical and geochemical characterisation of the surface sediments. However, previous studies stressed the importance of the two major sedimentological units (respectively marine (e.g. Aberta) and fluvial dominated areas (centre and interior of the lagoon)) to the lagoonal stratigraphy.

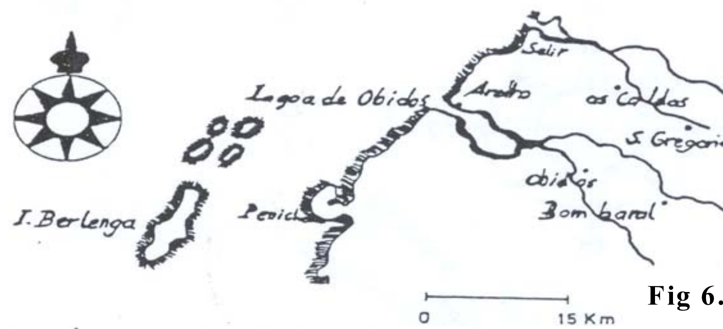

Fig 6.5 a

Fig 6.5 b

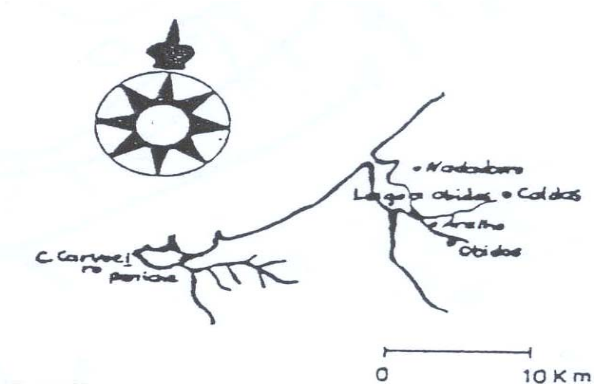

Fig 6.5 c

Figure 6.5- Historical maps of Lagoa de Óbidos (Freitas,1989a)

Figure 6.5a- Map of 1571

Figure 6.5b- Map of 1736

Figure 6.5c- Map of 1811

6.3- Geological setting

The knowledge of the regional geology will facilitate the study of the lagoonal sediments. The lagoon receives sediments eroded by the rivers and the sea. A group of natural conditions facilitate the intensive erosion (e.g. inclination of river channels; geological formations; littoral drift and the hydrodynamic of interface lagoon-sea).

The fluvial input is composed of sediments that are eroded by rivers (Cal, Arnóia and Real) while the marine input is composed of beach sand and sand dunes eroded by the sea and transported to the lagoon during high-tide or anomalous episodes (e.g. storm surges). Within Lagoa de Óbidos the transport is made by uniform suspension, except in the Aberta area where the transport is made my gradual suspension and dragging (Quintino & Rodrigues, 1985).

Moreover, the hydrographic network is small (approximately 410 km^2) and is composed of diverse formations from Quaternary sandstone to Jurassic limestone.

Using the Portuguese Geological Map, one can recognize that the drainage basin of the rivers that flow to Lagoa de Óbidos is composed by:

a) Dagorda Complex (Lower Jurassic), that consists of clay, marl, gypsum marls, dolomitic limestone and marl limestone, also detected are Lamellibranches and Gastropds fossils (outcrop in the Caldas da Rainha Valley);

b) limestone, marl limestone and marl schist belonging to the Middle Jurassic (outcrop in the Serra do Bouro and Sobral da Lagoa);

c) Montejunto and Alcobaça Layers, which consists of limestone, sandstone, marl and clay belonging to the Upper Jurassic (outcrop in the Planalto da Cesareda);

d) clayish sandstone and yellowish or redish sandstone and conglomerates belonging to the Upper Jurassic (outcrop in Foz do Arenho);

e) feldspatic sandstone occasionally with micaceous pebbles, belonging to Lower Cretaceous (outcrop in the western margin of Lagoa de Óbidos);

f) sand and sandstone with pebbles and clay clasts, belonging to the Upper Pliocene (outcrop in Caldas da Rainha Valley);
g) sand layers formed from old beach dunes and Quaternary terraces (outcrop in the left margin of Lagoa de Óbidos);
h) Calcareous tuft with fresh water molluscs and Neolitic ceramic (outcrop Olho Marinho);
i) sand dunes located north and south of Lagoa de Óbidos;

The diverse geology of the drainage basin is reflected in the sediments transported to the lagoon by River Cal, River Arnóia and River Real.
The interface Lagoa de Óbidos-Atlantic Ocean is limited, in Foz do Arelho (North margin of the lagoon), by two cliffs with different characteristics. The cliff located further north is the final stretches of the erosional area between S. Martinho do Porto and Lagoa de Óbidos. The cliff is formed by detritic deposits from the Jurassic (grey sandstone and brown conglomerates). The south cliff is composed of Cretaceous detritic deposits. Both cliffs exhibit strong erosional features.

In conclusion, it is obvious that the oceanic and fluvial actions contribute to the distribution of the lagoonal sediments. Sand is brought to the lagoon by sea waves, especially during high-tide, and finer sediments are transported to the lagoon by the rivers. One might conclude that the lagoonal sediments have marine origin, fluvial origin, aeolian origin (beach sand in Foz do Arelho) and biochemical sediments (formed inside the lagoon by chemical precipitation or by organic matter accumulation).

The Aberta is a detritic barrier composed of sand transported by the sea. This barrier limits the quantity of energy released by the sea waves, allowing a more peaceful sedimentological scenario in the interior of the lagoon. The Aberta retains most of the coarser material and only in exceptional storm surges coarser material is transported further inland. There are no records of the transport of sediments beyond the overwash fan, even in storm surges.

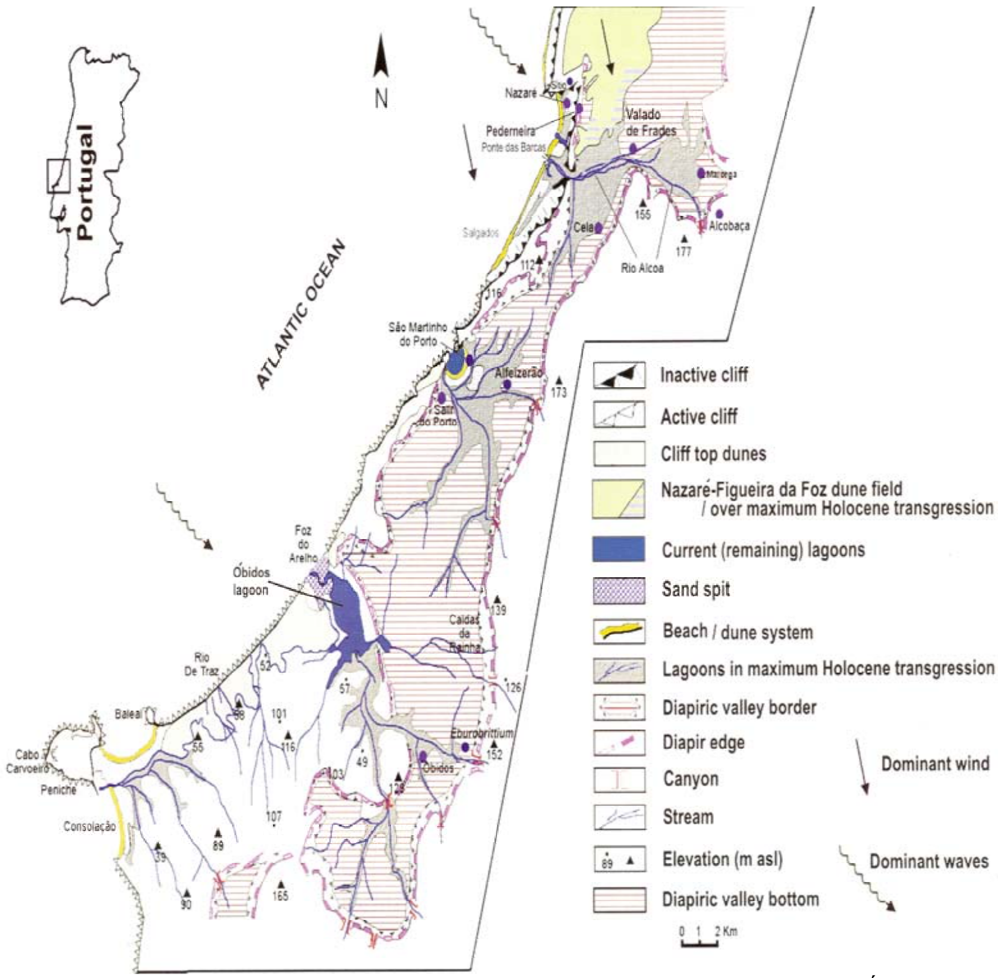

Figure 6.6- Geomorphological map of the coastal area surrounding Lagoa de Óbidos

(Dinis et al., 2006)

6.4- Results

6.4.1- Historical records

The historical records of the consequences of the AD 1755 Tsunami in Lagoa de Óbidos are almost non-existent. However, it is important to have in consideration that the area around the lagoon was not densely populated at the time. Moreover, the villages of Caldas da Rainha and the village of Óbidos (main population centres in the area) are located more than 5 kilometres inland and more than 40 metres above sea level; the Tsunami waves would not have sufficient energy to travel so far and so high. However, it is known that in the village of Óbidos the AD 1755 earthquake caused serious destruction, churches (S. Tiago and S. Pedro), the City Hall, the City Wall and many houses collapsed. Moreover, according to Sousa Moreira (1968) in Porto Novo, 25 km south of Óbidos, the run-up of the 1755 tsunami was 20 m and the penetration inland was 2.5 km. Porto Novo is a geomorphological area similar to Óbidos. Tsunami waves were also detected in coast of Figueira da Foz (75km North of Lisbon), in Porto and in other locations in the north-western coast of Portugal. There are no doubts that the AD 1755 Tsunami waves affected many coastal areas along the Portuguese coast. One can undoubtedly assume that the tsunami waves also affected the coast of Óbidos.

6.4.2- Coring

Four cores (approximately 130 cm long each) were collected from Lagoa de Óbidos using a Livingstone (piston) corer in October 2002. A transect with an orientation NNW-SSE (Fig. 6.7) was followed. The cores were wrapped in plastic film to prevent changes of water content and stored in PVC pipes after extrusion. Altitude and water depths were measured with a GPS in each station (See Table 6.1).

Core	Sections	Water Depth (cm)	Altitude of lagoon bed (above sea level) (cm)
OB1	3	200	500
OB4	2	210	500
OB5	1	180	480
OB2	2	150	400

Table 6.1- Core sections, water depth and altitude of Óbidos cores measured in the boat.

Figure 6.7 - Aerial photo of Lagoa de Óbidos and core locations
(adapted from Serviços Nacionais de Informação Geográfica, 2001)

6.4.3- Stratigraphy

The standard core description was conducted, according with the Ocean Drilling Program visual core description form, included granulometry, macroscopic sedimentary structures, the nature of contact between different stratigraphical units and colour (according to the Munsell colour chart). Four different stratigraphic Units were identified (Figure 6.8).

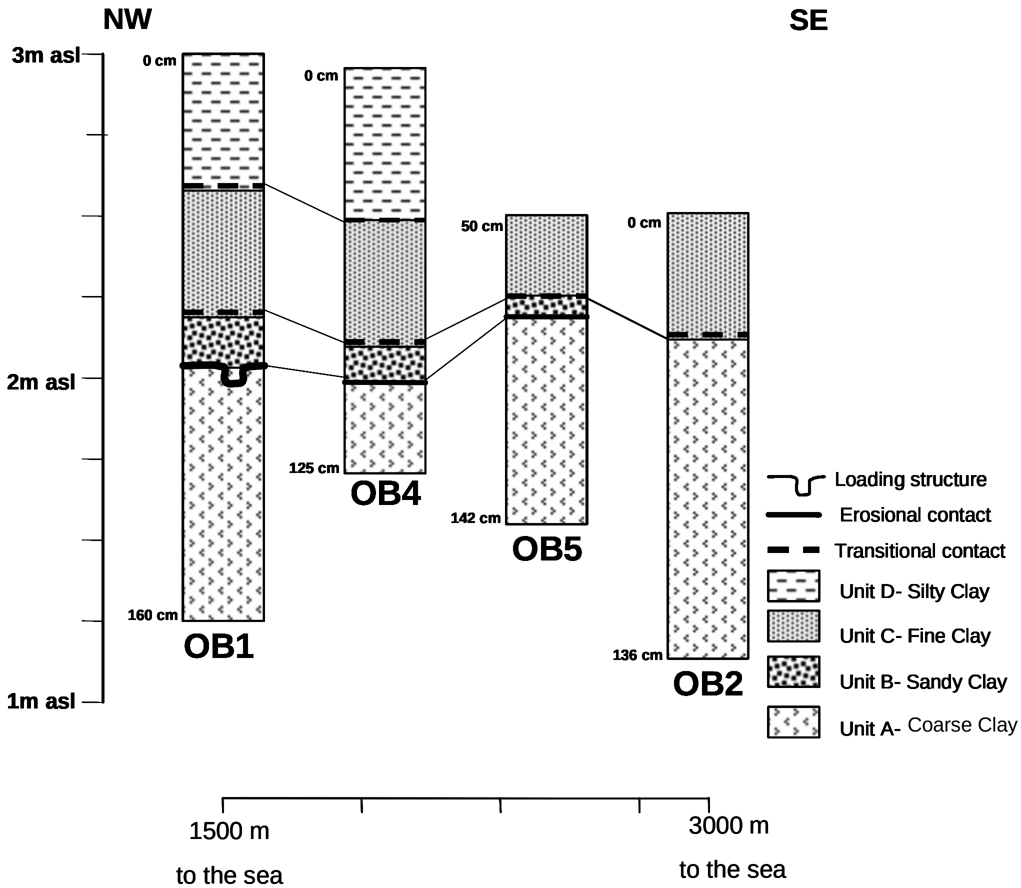

Figure 6.8- Schematic lithostratigraphy of Lagoa de Óbidos cores

Unit A, the deepest unit, consists of coarse clay, darker in the eastern stations and present in all. In places this unit contains a discontinuous milimetric scale laminae of dark brow clay interlayed with light brown clay. The contact between Unit A and the overlying Unit B is erosional.

Unit B, the Event Unit, consists of olive green sandy material, which fines inland. Moreover, it is not present on Station 2, the most eastern station. The shell richness of this unit was also evident. A load cast was also recognised on the base of this unit on core OB1.

Unit C, overlying Unit B, consists of very fine clay, without any visible sub-units, is present in all stations. The contacts between Unit C and the over and underlying units are transitional.

The top unit, Unit D, only present on the two westernmost stations, consists of clay\silt material that becomes coarser towards the top. In places it was also possible to identify some laminae, alternating coarser, light milimetric silt\clay material with finer, darker clays.

The stratigraphy of the cores represents the complexity of the depositional system in Lagoa de Óbidos. The marine influence is clearly noticed on stations 1 and 4, and less relevant on stations 5 and 2. Each unit represents different depositional conditions, related with the balance between the marine and fluvial deposits. The abruptness of the contact between Unit A and B suggests a sudden, high-energy and short-lived depositional event.

6.4.4- Magnetic Susceptibility

Magnetic susceptibility measurements were conducted on unopened cores. Daily measurements were made during the coring campaign. The procedure followed was described in Chapter 5. The results allowed the correlation, especially between OB2, OB4 and OB5 (Figure 6.9). The results obtained on OB1 were very low and no correlation with the other cores was possible, except partially with OB4. However, in OB1 it was noted that a high peak was presented and after stratigraphic description correspondence was possible with the limit between units D and C (Figure 6.10). Magnetic susceptibility measurements on core OB4 exposed a peak at the base of Unit B (event unit). On core OB5 the measurements revealed two peaks; one at the bottom of Unit B; other, around 130cm deep which corresponds with another event, later detected in granulometry. Results from core OB2 revealed correspondence between the lowest values and the limits of Units C and A. Another event was also detected on core OB2, with a peak approximately around 110cm deep.

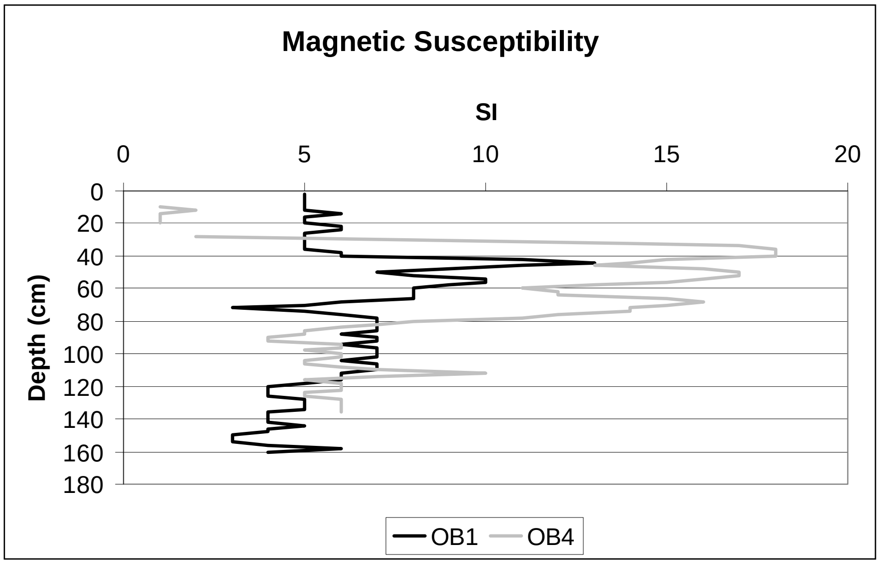

Figure 6.9- Magnetic susceptibility results for OB1 and OB4

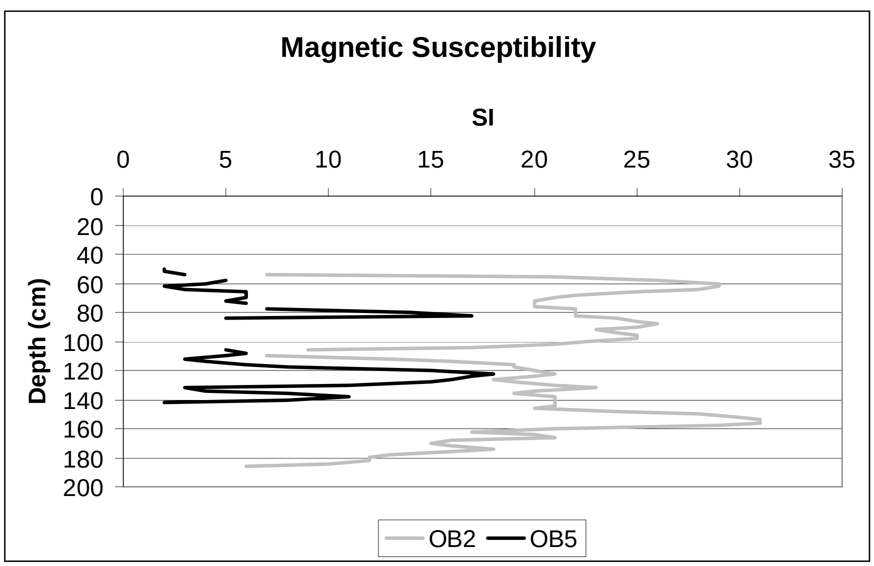

Figure 6.10- Magnetic susceptibility results for OB2 and OB5

6.4.5- X-ray and digital photography

X-ray photographs were made of selected intervals to reveal sedimentary structures. X-rays were used to highlight features that are not visible by visual description. The results of both digital and x-ray photos are presented in Figure 6.11 and 6.12. The strong contrast between Unit A and B was exposed on both analyses. The shell (many of them broken) richness of Unit B was highlighted in the x-ray photos.

Figure 6.11- Digital photo of Unit B from OB1.2

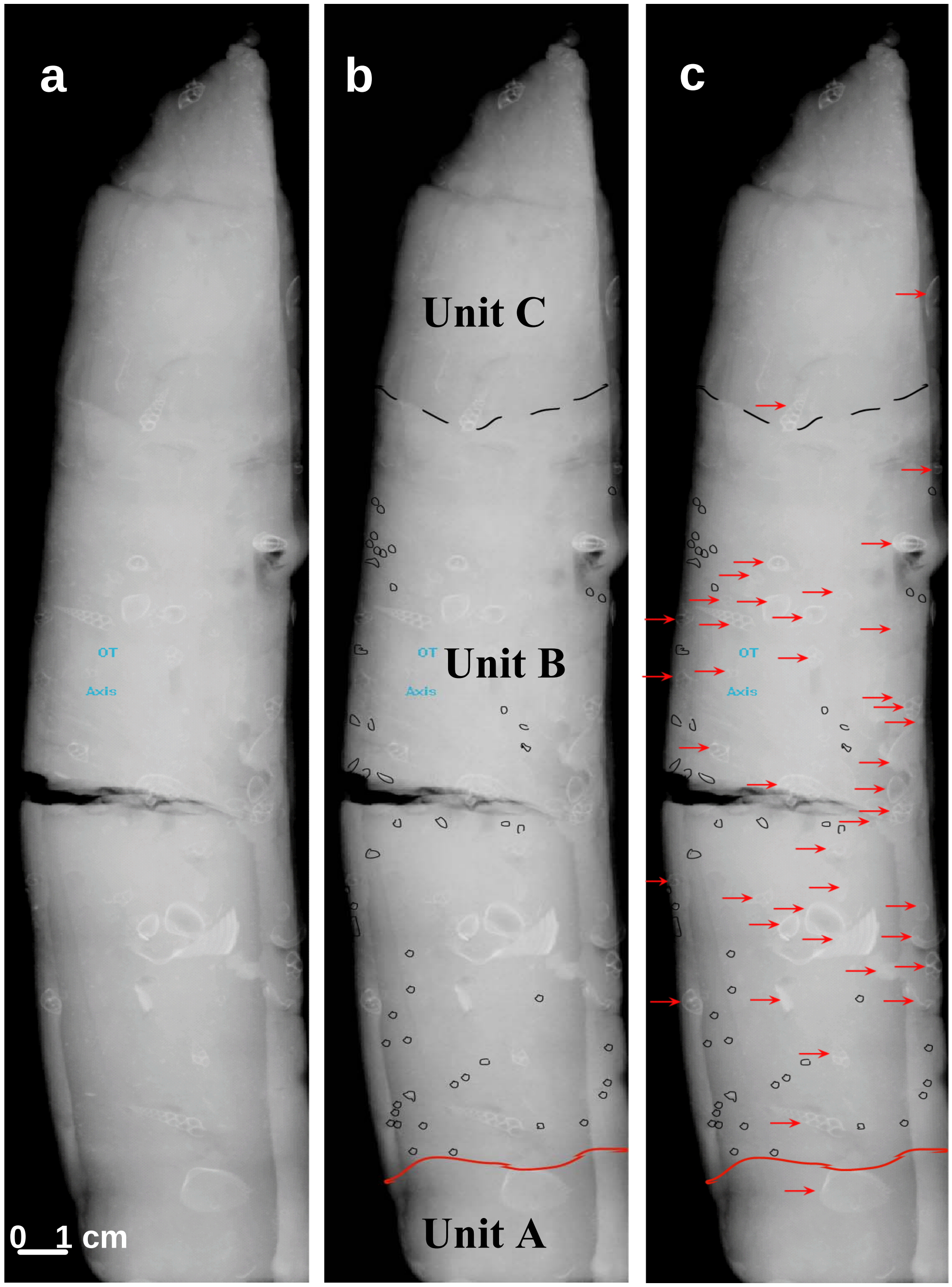

Figure 6.12- X-ray photography of Unit B from OB4.
Black circles indicate coarser clasts and arrows indicate fossils.

6.4.6- Geochemical analysis

Loss on ignition was conducted in order to determine organic matter content and carbonates content. The results indicated a continuous decrease of organic matter in OB1 and OB5 and a continuous increase in OB2 and OB4 (Figures 6.13 and 6.14). The organic content on core OB1 revealed a sharp change just under the contact between Unit D and Unit C. Unit B is marked by a slight decrease in the organic matter content. The core OB4 presented a continuous increase and a sharp increase in the contact between Unit D and the overlying Unit C. The organic content on core OB5 exhibited a persistent decrease from bottom to top, as well as a slight increase at the bottom of Unit B. Core OB2 presented a continuous increase of the organic matter content.

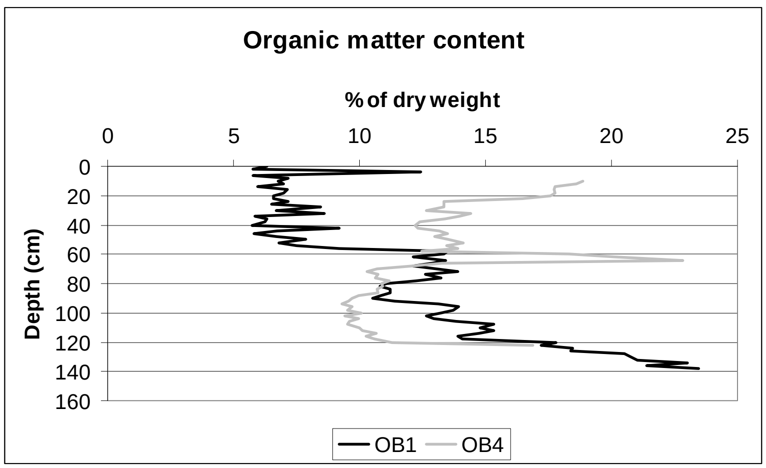

Figure 6.13- Organic matter content of OB1 and OB4.

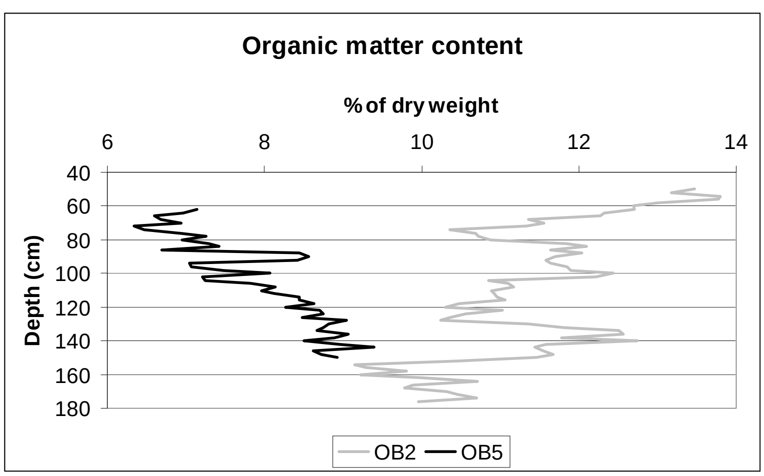

Figure 6.14- Organic matter content of OB2 and OB5.

The following proxy is the measurement of the carbonates content (Figures 6.15 and 6.16). On core OB1 the carbonates content decreases progressively towards the top but has 4 major exceptions with sharp increases at approximately 100 , 60, 20 and 5 cm deep (e.g. bottom of Unit B; limit between Unit D and Unit C; two more recent events around 20 and 5 cm deep). The carbonates content on core OB4 presented a similar behaviour to OB1, with the exception of Unit B which did not present any sharp increase. OB2 and OB5 present similar patterns of carbonates content, with the exception of a sharp increase around 100cm deep in OB2, where Unit B is not present in the stratigraphy.

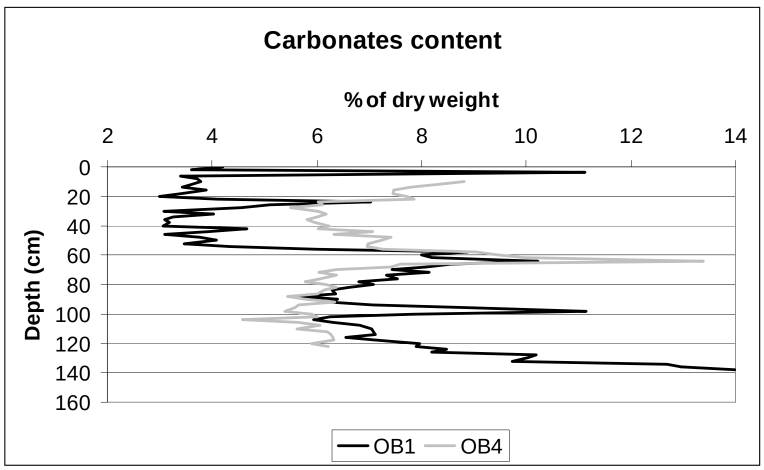

Figure 6.15- Carbonates content on core OB1 and OB4.

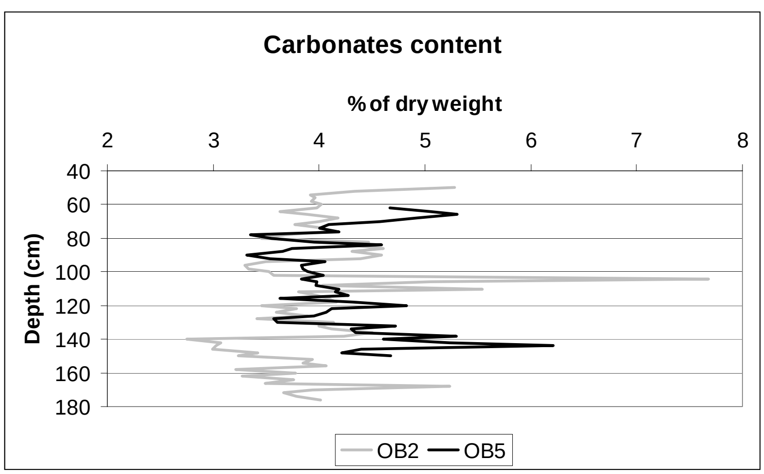

Figure 6.16- Carbonates content on core OB2 and OB5.

Atomic Absorption Spectroscopy (AAS) was conducted at a 2 cm interval in all cores from Lagoa de Óbidos. The following elements were analysed: Al, Ca, Fe, K, Mg, Mn, Na, Pb and Zn. The ratios Fe/Mn and Mg/Ca were also calculated. An extensive and complex set of data was produced. Forty four charts were plotted and analysed. Based on the extensive data produced some conclusions were made. To better visualise the geochemical conclusions Tables 6.2, 6.3, 6.4 and 6.5 and Figure 6.17 and 6.18 are presented below.

Element	Core OB1
Al	1) Base of Unit B presents sharp increase 2) Continuous decrease to the top of core 3) Slight decrease at base of Unit C
Ca	1) Oscillations (slight increases) at the base of Unit D and Unit B and at 120 cm
Fe	1) Continuous decrease towards the top of core 2) Sharp increases at Unit B (3 peaks) and Unit D (1 peak)
K	1) Continuous decrease towards the top of the core 2) Sharp increase (3 peaks) at Unit B
Mg	1) Continuous decrease towards the top of the core 2) Sharp increases at Unit B (3 peaks) and at 120 cm (1 peak)
Mn	1) very low concentrations 2) continuous decrease towards the top 3) Peak at base of Unit B
Na	1) Continuous decrease towards the top of the core 2) Sharp increase at of Unit B (3 peaks)
Pb	1) very low concentrations 2) Oscillations present but without stratigraphic correlation
Zn	1) Extremely low concentrations 2) Peak at base of Unit B and at 120 cm
Fe/Mn	1) Frequent oscillations but no evident correlation with stratigraphy
Mg/Ca	1) Frequent oscillations but no evident correlation with stratigraphy

Table 6.2- Major conclusions of geochemical analyses on core OB1.

Element	Core OB4
Al	1) Increase towards the top 2)Base of Unit B marked by peak but base of Unit D marked by decrease
Ca	1) Frequent oscillations but no correlation with stratigraphy was established
Fe	1) Frequent oscillations 2) Peak at base of Unit B
K	1) Frequent oscillations 2) Two peaks at Unit B
Mg	1) Frequent oscillations 2) Peak at base of Unit B
Mn	1) Frequent oscillations but no correlation with stratigraphy was established
Na	1) Frequent oscillations 2) Increase towards the top 3) Unit B marked by 3 peaks
Pb	1) Extremely low values 2) Increase towards the top
Zn	1) Frequent oscillations but no correlation with stratigraphy was established
Fe/Mn	1) Frequent oscillations but no correlation with stratigraphy was established
Mg/Ca	1) Frequent oscillations 2) Peaks at base of Unit B and Unit D

Table 6.3- Major conclusions of geochemical analyses on core OB4.

Element	Core OB5
Al	1) Frequent oscillations but no correlation with stratigraphy was established
Ca	1) Five peaks present (one coincident with base of Unit B)
Fe	1) Frequent oscillations but no correlation with stratigraphy was established
K	1) Major peak at base of Unit C
Mg	1) Major peak at base of Unit C
Mn	1) Extremely low values 2) Peaks at base of Unit C, Unit B and app. at 120 cm
Na	1) Frequent oscillations but no correlation with stratigraphy was established
Pb	1) Extremely low values 2) Frequent oscillations but no correlation with stratigraphy was established
Zn	1) Increase towards the top of core 2) Frequent oscillations but no correlation with stratigraphy was established
Fe/Mn	1) Frequent oscillations but no correlation with stratigraphy was established
Mg/Ca	1) Increase towards the top 2) Peak at base of Unit B and at app. 120 cm

Table 6.4- Major conclusions of geochemical analyses on core OB5.

Element	Core OB2
Al	1) Increase towards the top of core 2) Peaks around app. 60, 80 and 120 cm 3) No correlation with stratigraphy was established
Ca	1) Frequent oscillations 2) Peaks around app. 60, 80 and 120 cm 3) No correlation with stratigraphy was established
Fe	1) Frequent oscillations 2) Increases around app. 60 (1 peak), 80 (2 peaks) and 120 cm (2 peaks) 3) No correlation with stratigraphy was established
K	1) Frequent oscillations 2) Sharp increase around app. 60 cm 3) No correlation with stratigraphy was established
Mg	1) Frequent oscillations 2) Peaks around app. 60, 80 and 120 cm 3) No correlation with stratigraphy was established
Mn	1) Frequent oscillations 2) Peaks around app. 80 and 120 cm 3) No correlation with stratigraphy was established
Na	1) Increase towards the top of core 2) Peaks around app. 60, 80 and 120 cm 3) No correlation with stratigraphy was established
Pb	1) Frequent oscillations 2) Extremely low values 3) No correlation with stratigraphy was established
Zn	1) Frequent oscillations 2) Extremely low values 3) Peaks at base of Unit C and app. at 60, 80 and 120 cm
Fe/Mn	1) Frequent oscillations 2) No correlation with stratigraphy was established
Mg/Ca	1) Frequent oscillations 2) Sharp decrease after app. 100cm

Table 6.5- Major conclusions of geochemical analyses on core OB2.

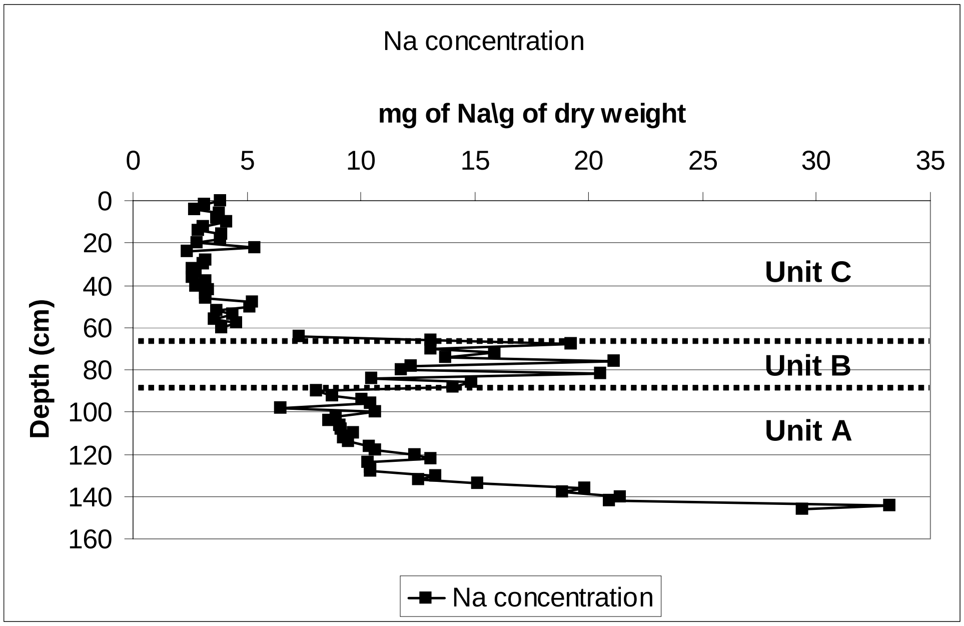

Figure 6.17- Na concentration on core OB1 (Unit B and underlying and overlying units)

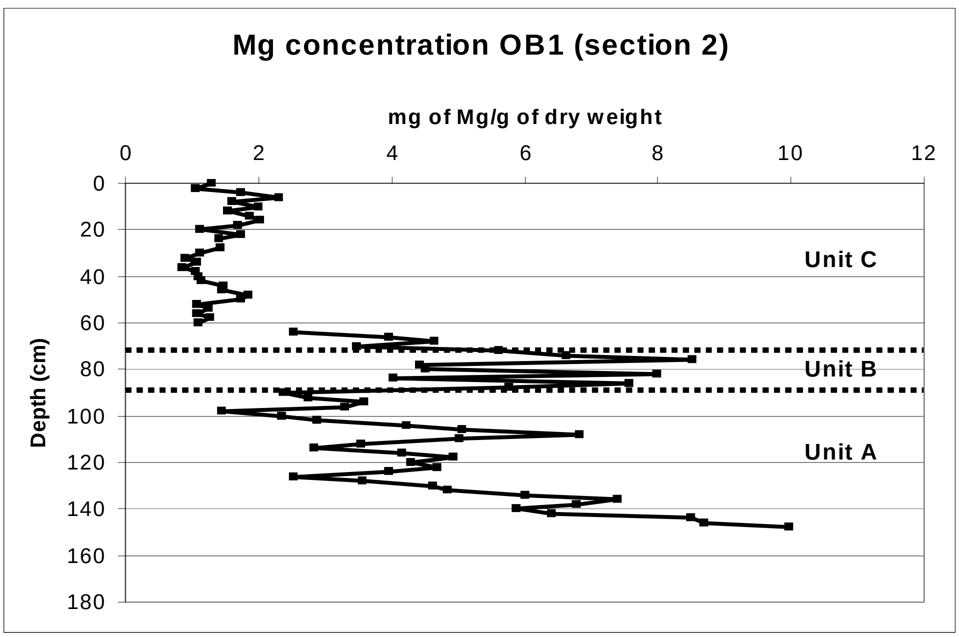

Figure 6.18- Mg concentration on core OB1 (Unit B and underlying and overlying units)

The complexity and wide range of results obtained will be later discussed in Chapters 8 and 9.

6.4.7- Grain size analysis

Grain size analyses were conducted using laser granulometry (Malvern 2000 Series Laser) at the University of Gloucestershire. All cores from Óbidos were analysed at a 5 cm interval. Unit B was analysed at a 1 cm resolution (Figure 6.19). For all cores, charts presenting percentage of sand, clay and silt, average grain size and mode were plotted. Standard deviation, kurtosis and skewness were also calculated.

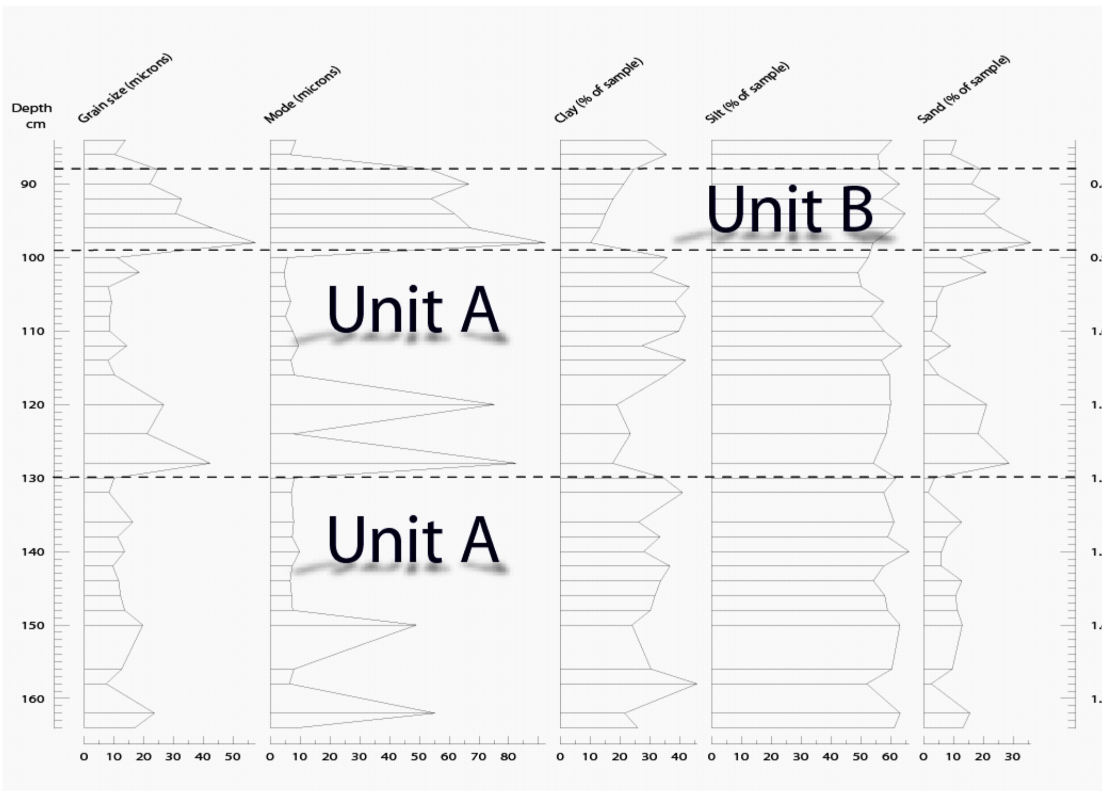

Figure 6.19- Grain size analysis of Unit A and B on core OB1

The results indicated a silt-dominated material in the cores. Furthermore, the results showed three major events, with sharp increases in grain-size, at base of Unit B, at app. 60 cm and at app. 120 cm (Figure 6.19 and Figure 6.20). The grain-size analysis also demonstrated that the event unit (Unit B) fines upwards. A sequence of 3 fining upward sub-units was clear in OB1 (Fig 6.19). Moreover, the average grain size of Unit B decreases towards the east demonstrating the loss of energy of the abrupt depositional event responsible for its deposition. Statistical grain size parameters (e.g. standard deviation, skewness and kurtosis) were calculated, using formulas based on MacManus (1988). However the results were complex and no correlation was possible with stratigraphy. The granulometric data nevertheless confirmed the uniqueness of Unit B in the lithostratigraphy of Lagoa de Óbidos.

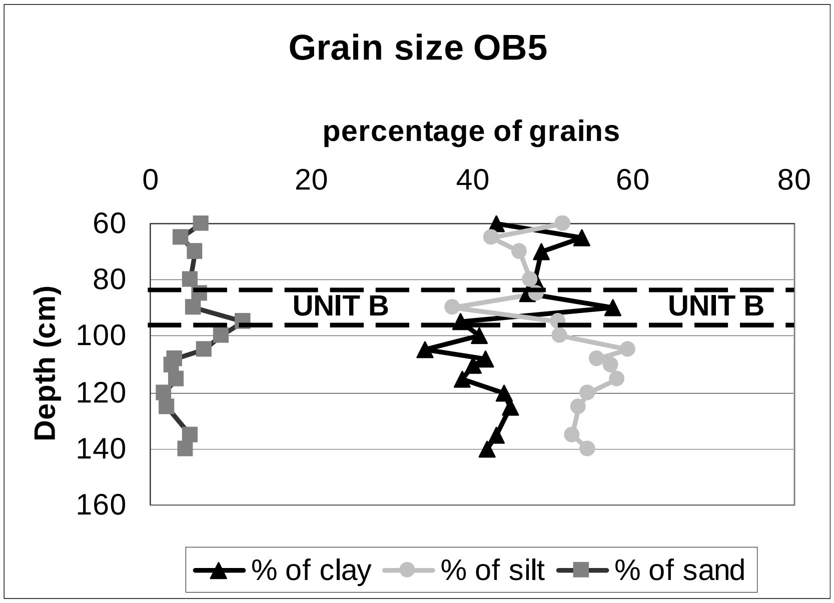

Figure 6.20- Clay, silt and sand content on core OB5.

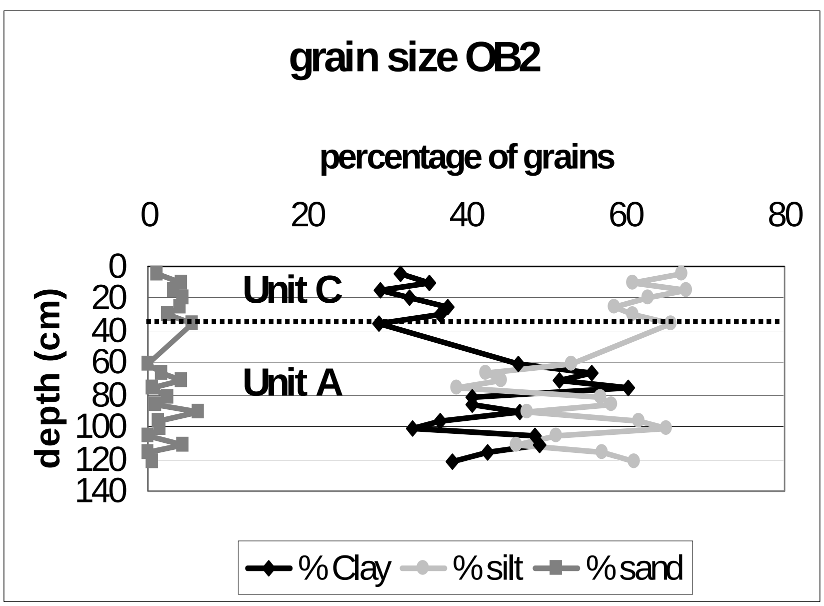

Figure 6.21- Clay, silt and sand content on core OB2.

6.4.8- Palaeontology

A brief palaeontological study was conducted. Macrofossils were analysed with a magnifying glass in section OB 1.2. Particular focus was directed to the event unit and the immediate underlying and overlying layers. Results showed clear changes in the palaeontological features of these units. Unit B has a richer and more diverse palaeontological content when compared with the underlying and overlying layers.

Samples were mainly composed by Molluscs, Foraminifera, Ostracods and plant debris. Marine to brackish Molluscs species were identified (e.g. *Cerastoderma edule*, *Pavicardium exiguum*, *Rissoa parva*, *Turritella communis*). No major change in Molluscs content was detected, neither in the total number of species or in the number of specimens.

However, other macrofossils changes were noted. The event layer is richer in twig/roots, plant fragments and shell fragments indicating a strong energy event. Additionally, it was also detected a decrease in the number of ostracods at the base of Unit B (Figure 6.22). Furthermore, the presence of large quantities of quartz in Unit B is also a strong indicator of the marine character of the deposit.

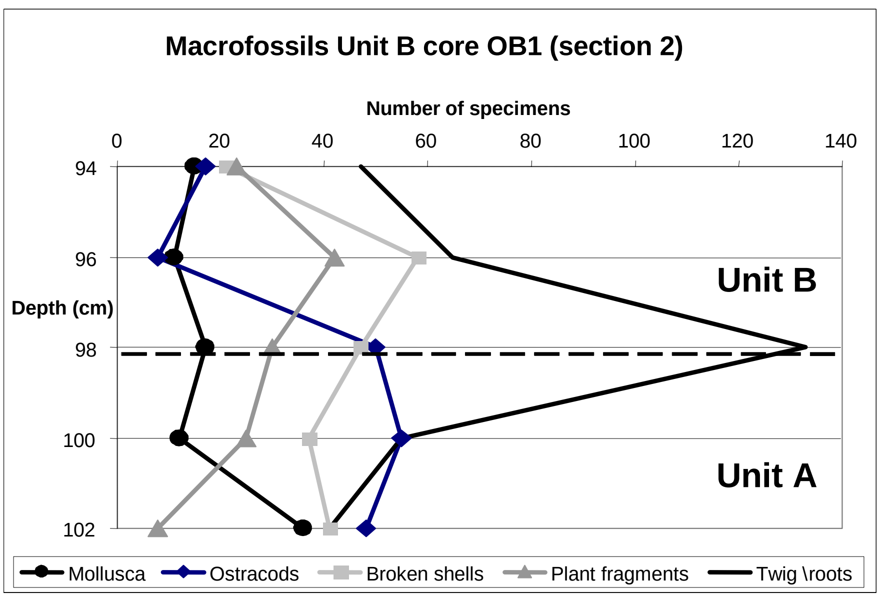

Figure 6.22- Macrofossils content of Core OB1 (section 2)

6.4.9- Dating results

Optically Stimulated Luminescence (OSL) was used to date the base of Unit B from core OB1 (section 2). The method described in Chapter 5 was followed and the age obtained for Unit B was 136±17 years (Figure 6.23 and Table 6.6). Radiocarbon date was not use due to the uncertainties obtained in the results for this very recent time frame.

Sample	OB1 (base of Unit B)
Total wet γ dose rate (Gy.ka^{-1})	0.83±0.14
Neutron Activation Analysis K (%)	2.09±0.10
Neutron Activation Analysis Th (ppm)	10.05±0.52
Neutron Activation Analysis U (ppm)	3.25±0.16
Total wet β dose rate (Gy.ka^{-1})	1.28±0.21
Cosmic dose rate (Gy.ka^{-1})	0.18±0.02
Total dose rate (Gy.ka^{-1})	2.30±0.25
Dosimetry (Gy)	0.31±0.02
Age (years)	**136±17**

Table 6.6- Dosimetry and Age data obtained for Unit B.

Lead 210 analyses were conducted at the Department of Geography and Earth Sciences, Brunel University. Method followed was presented in Chapter 5. The results indicated a sedimentation rate for the top of core OB4 of approximately of 9 mm/year (Figure 6.24 and Figure 6.25). Extrapolating the results obtained with OSL and with ^{210}Pb dating one can calculate sedimentation rates. Sedimentation rate obtained with OSL was approximately 7 mm/year. The dating results are discussed in Chapter 8.

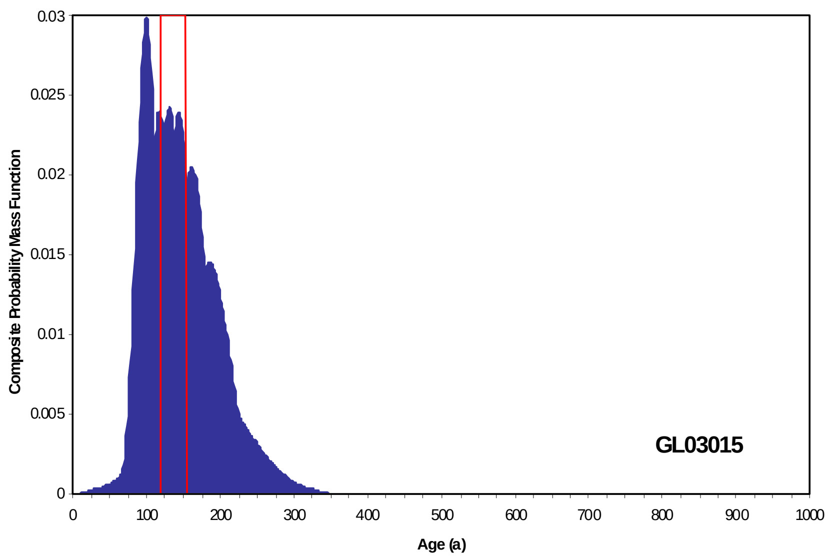

Figure 6.23- Composite probability mass function showing the age estimates generated by 12 125-180 µm aliquots of OB1 (section 2). Red vertical lines delimit the 1 σ standard error range about the geometric mean age value.

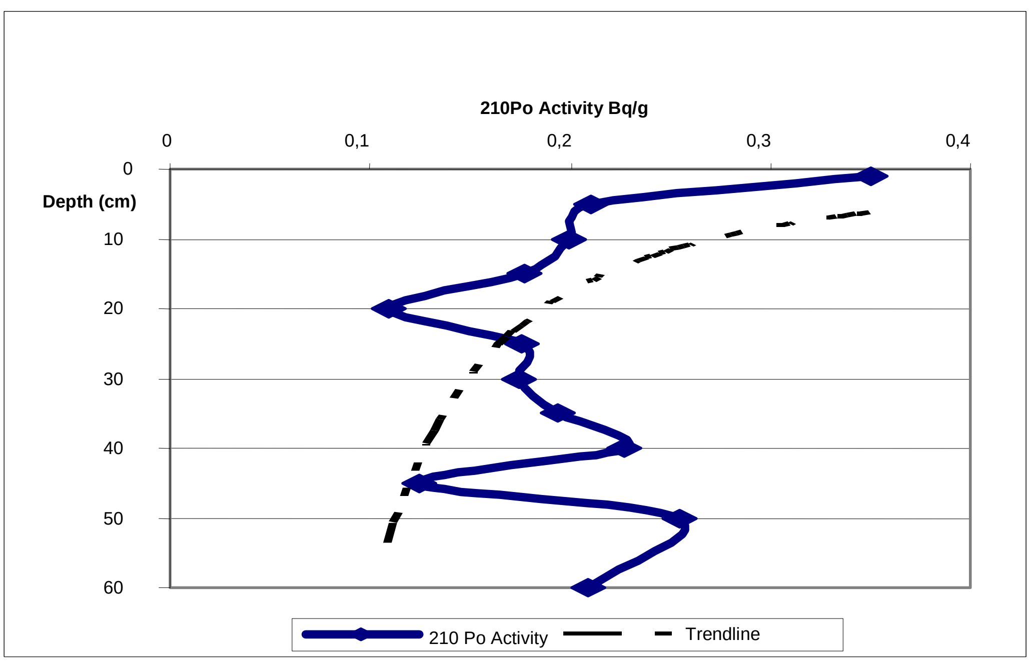

Figure 6.24-^{210}Pb unsubstantiated values and trend line predicted for OB4.

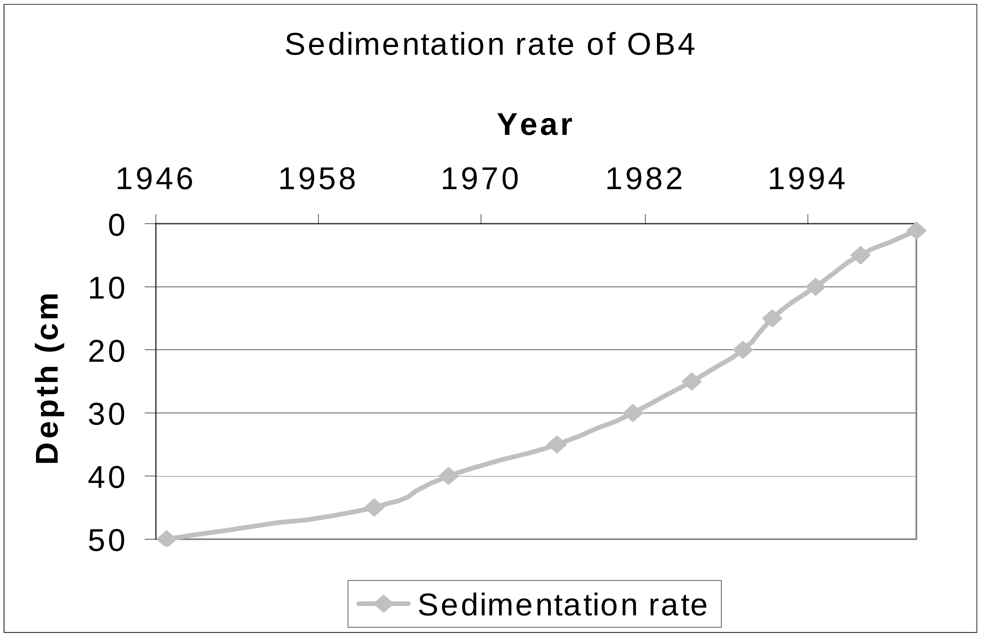

Figure 6.25- Sedimentation rate of OB4.

6.5- Conclusion

The complexity of the stratigraphical environment of Lagoa de Óbidos was demonstrated by this research.

Differentiating tsunami and storm deposits was possible only due to the extension inland and the stratigraphic signature of the events. In addition, it was once obvious the difficulties of the differentiation of units deposited by abrupt marine invasions. The specific characteristics of Lagoa de Óbidos had a major role in the conclusions achieved.

Some conclusions were accomplished:

1- The fluvial and marine influences in the sedimentological cores were obvious.

2- Lagoa de Óbidos presents 3 sedimentological major events (at Unit B, at approximately 60 cm and at approximately 120 cm).

3- Unit B exhibits many of the tsunamigenic diagnostic characteristics and is the only event with stratigraphic signature (later discussed in Chapter 8).

4- Organic matter content decreased and carbonates content increased at base of Unit B.

5- Within each of the 3 events geochemical and granulometry results were correlated.

6- Elements such as K and Mg were good indicators of marine invasions (increases in average grain size).

7- Palaeontology revealed the high-energy of the event that deposited Unit B.

7. Martinhal

7.1- Introduction

The AD 1755 tsunami affected particularly the south coast of Portugal. A small amount of eyewitnesses described the effects of the tsunami waves along the Algarve coast.

Martinhal, located in the south-western costal area of the Algarve, is a small valley separated from the sea by a sand barrier. According to historical records the AD 1755 tsunami was observed in Martinhal.

Kortekaas (2002) conducted a group of palaeoenvironmental proxies to detect a tsunamic unit deposited by the AD 1755 tsunami in Martinhal. The research proved the existence of one unit laid down by the AD 1755 and the presence of multiple sand layers attributed to storm surges.

Permission was granted by Kortekaas to study one core (Mart 27) and look for traces of the AD 1755 tsunami deposit and to compare it with other units possible deposited by tsunamis or storm surges. No proxy was conducted in Mart 27 prior to this research and the results are presented in this chapter.

7.2- Previous studies

Kortekaas (2002) conducted palaeotsunami research in Martinhal. Stratigraphic, granulometric and palaeontological studies were conducted. Cores were collected and trenches were opened. The author concluded that the AD 1755 tsunami had a major impact on the geomorphology and sedimentology of Martinhal. The tsunami breached the barrier and laid down an extensive sheet of sand containing many shell fragments, pebbles, mudballs and large boulders. Kortekaas (2002) also detected multiple sand layers resulting from the frequent flooding by storm surges. The differentiation of tsunami and storm units was only possible in trenches. The cores obtained did not present major tsunami characteristics (e.g. boulders, rip-up clasts). The foraminiferal analysis conducted revealed that storm surges have similar assemblages, even if the tsunamic unit has higher concentrations. One major tsunamic characteristic detected by Kortekaas (2002) was the fact that the inland extent of the tsunami unit exceeds that of any other sand deposit. The grain size analysis proved the coarser content of any tsunamic or storm surge deposit. However, granulometry was not conclusive in terms of differentiating tsunami and storm deposits. Stratigraphic analysis, palaeontological studies and dates obtained for the tsunami deposit will be discussed in this chapter.

7.3- Geological setting

Martinhal lowland is a small triangular shaped floored estuarine valley situated on the southern Algarve coast near Sagres (Figure 7.1).

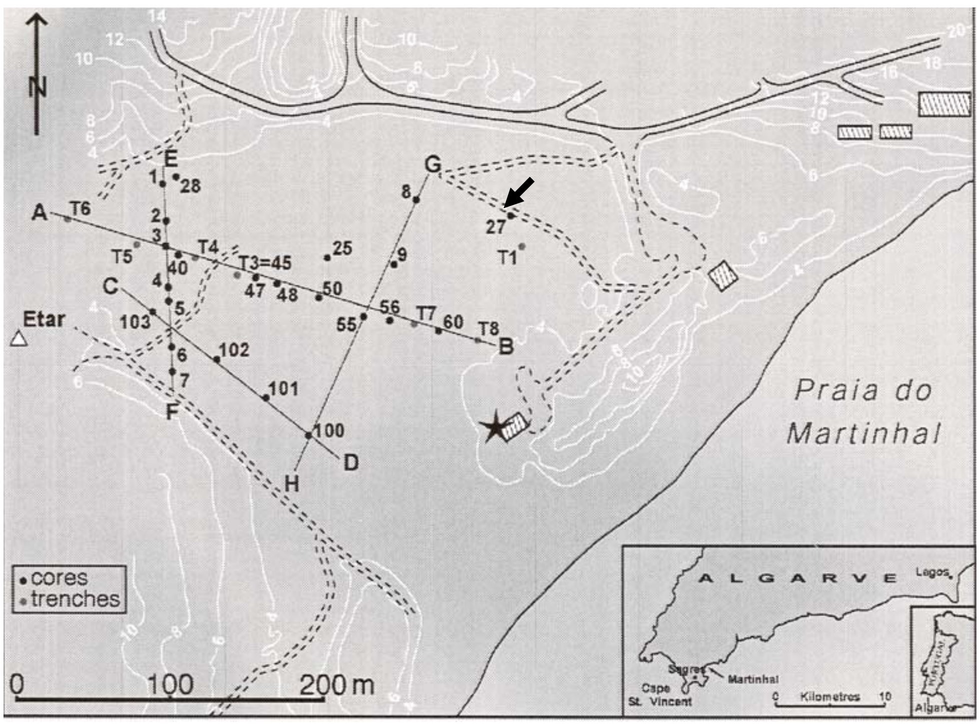

Figure 7.1- Location of Martinhal. Location of trenches and cores collected. Benchmark indicated by the star. Profile lines presented (A-B; C-D; E-F; G-H). (Kortekaas, 2002)

It is formed by two small streams, cutting the upper Jurassic limestone. The largest stream, Barranco das Mós enters the valley from the NW and a smaller stream enters from the north. The lowland is separated from the sea by a barrier consisting of sand dunes and a sand beach. The barrier is normally a continuous feature throughout the year and the lowland is a saltmarsh swamp, which dries out in the summer but is periodically flooded by river water during the winter. Short episodes of marine flooding occur when the barrier is breached during storms. In the centre of the lowland the surface consists of silt with saltmarsh vegetation. At the outer edge and in the higher NE part of the lowland, the surface is sandy with very little vegetation except for some grass. In the NW, close to the stream outlet a small alluvial fan is present. The tidal range in the area is approximately 2.1 m and is about 3 m during spring tides. During extreme spring tides the high tide level may exceed 2 m above MSL (Andrade & Hindson, 1999).

7.4- Results

7.4.1- Historical records

The following description of the flooding of Martinhal was given by Silva Lopes (1841), discussed by Pereira de Sousa (1919) and translated by Andrade et al. (1997): (original words between commas and translation or additions in brackets).

"The sea flooded a beach called "Mortinhal", facing eastwards, by about ½ league (circa 2 km), ripping off vineyards and leaving the land as if it was a beach, covered by several types of fish and big "penedas" (large boulders) of which one, weighting more than 300 "arrobas" (circa 4500 kg) showed many shellfish stuck on its surface. Three times the sea struck and withdrew, the first wave being the largest."

7.4.2- Coring

Mart 27 was collected by Dr Stella Kortekaas in 1997. An Eijkelkamp hand gouge auger with a 3 cm diameter chamber was used to study the stratigraphy and a 10 cm gouge auger was used to take samples. In order to recover sand under the water table a Van der Staay suction corer was used. Mart 27 was collected in the north-eastern area of Martinhal (Figure 7.1)

7.4.3- Stratigraphy

Mart 27 is characterised by the presence of four stratigraphic units (Figure 7.2). Those four units can be correlated with the lithostratigraphic units presented by Kortekaas (2002) for other cores and trenches collected in Martinhal.

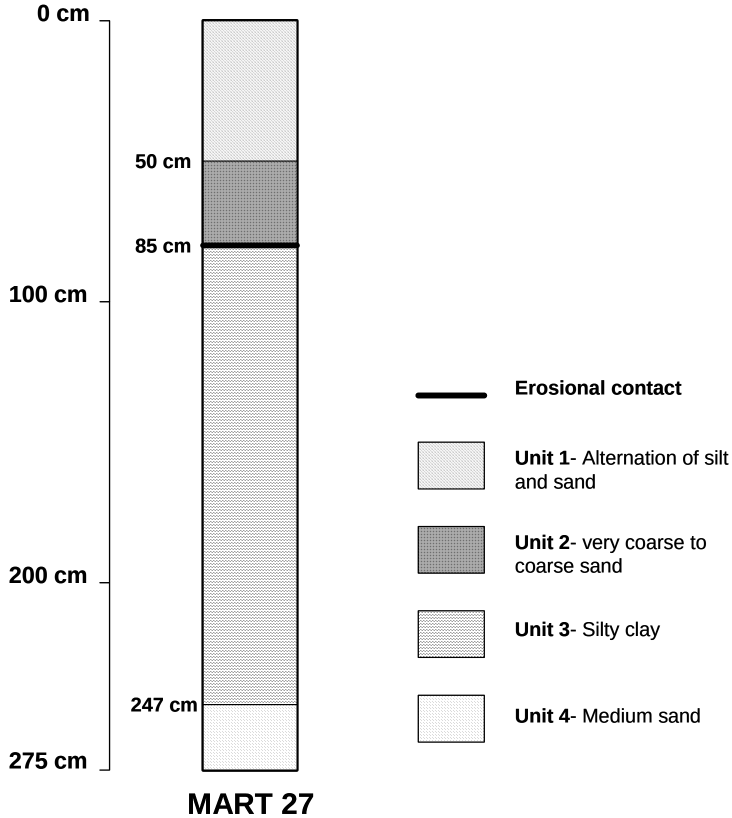

Figure 7.2- Schematic stratigraphy of Mart 27

The top unit (Unit 1) consists of several sandy and silty sub-units. The sub-units have different thicknesses. Furthermore shell fragments were detected. Unit 1 has a thickness of 50 cm.

Unit 2 is composed of very coarse to coarse sand. Shell fragments and rip-up clasts are present. Moreover, the lower contact is erosive. Apparently, the Unit fines upwards. The thickness of Unit 2 in Mart 27 was of 35 cm.

Unit 3 is the longest unit of Mart 27 with approximately 190 ccm. Unit 3 consists of light brown silty clay.

The bottom unit of the stratigraphic sequence (Unit 4) presents medium sand with some shell fragments.
Similar features were detected in some sub-units within Unit 1 and Unit 2.

7.4.4- Magnetic susceptibility

Magnetic susceptibility measurements were conducted on core Mart 27. Results exhibited several oscillations that were not related with the stratigraphic units. Unit 2 presents decreasing values and its base is not marked by any sharp increase, while Unit 3 presents increasing higher values towards the top of the Unit. Unit 1 was not analysed because the sample was not stored in a PVC pipe but in sample bags which made impossible to conduct any magnetic susceptibility analyse.

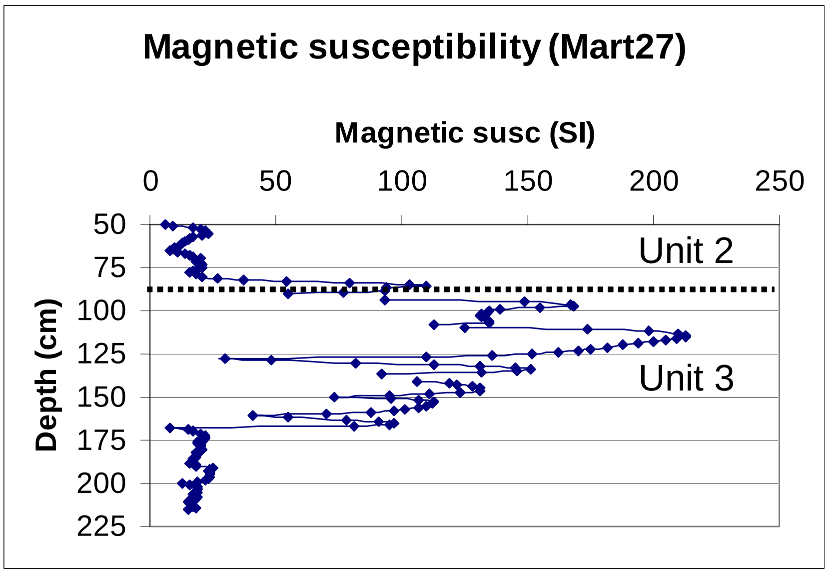

Figure 7.3- Magnetic susceptibility results of Mart 27.

7.4.5- X-ray and digital photography

Several digital photos and one x-ray photography were taken from core Mart 27. The x-ray image focused on the limit between Unit 3 and Unit 2. A comparison between both photos is presented. The sharp contact between the Unit 2 and Unit 3 was noted and a rip-up clast was detected within Unit 2 (Figure 7.4, Figure7.5).

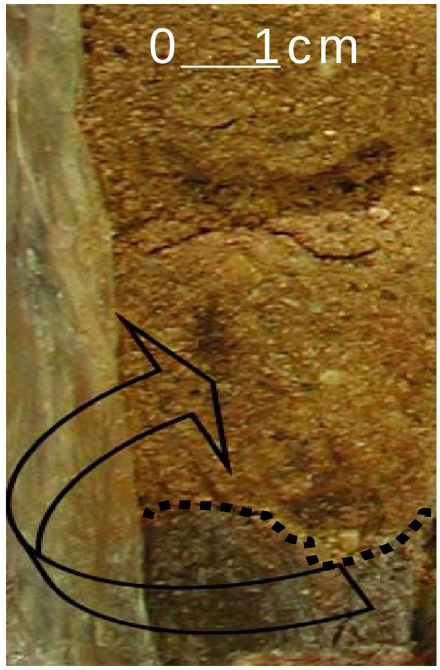

Figure 7.4- Digital photography of Mart 27. Contact between Unit 3 and Unit 2 (dashed line). Rip-up clasts were detected (arrow).

Figure 7.5- X-ray photography of Mart 27 (Base of Unit 2).

7.4.6- Geochemical analysis

Loss on ignition, Atomic Absorption Spectroscopy (AAS) and X-Ray Fluorescence (XRF) analyses were conducted on core Mart 27.

Loss on ignition revealed a sharp decrease of the organic matter content and a sharp increase of carbonates at the base of Unit 2. Overlying Unit 2 a small increase in carbonates and in organic matter was detected (Figure 7.6).

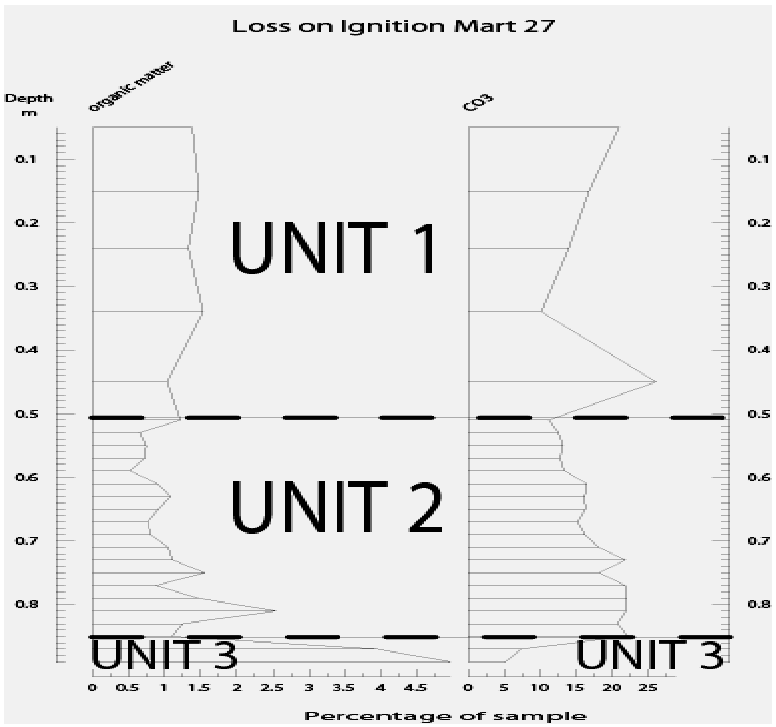

Figure 7.6- Loss-on- ignition results of Mart 27.

AAS analyses were conducted to detect the concentration of Ca, Fe, K, Mg, Mn, Na and Pb on the top meter of core Mart 27. Results are presented in Table 7.1, Figure 7.8 and Figure 7.9. Results demonstrated correlation with stratigraphic signature. Increases in the concentration of Ca, Fe, K, Mg and Na were detected. Mn exhibited a particular behaviour with maximum values at the bottom and top of Unit 2. Pb concentration did not show any correlation with stratigraphy.

Element	Core Mart 27
Ca	1) Decrease towards the top 2) Highest value at bottom of Unit 2
Fe	1) Decrease towards the top 2) Sharp increase at bottom of Unit 2
K	1) Decrease towards the top 2) Sharp increase at bottom of Unit 2
Mg	1) Frequent oscillations 2) Highest value at bottom of Unit 2
Mn	1) Two peaks at bottom and top of Unit 2
Na	1) Decrease towards the top 2) Sharp increase at bottom of Unit 2
Pb	1) Extremely low values. No correlation with stratigraphy

Table 7.1- Summary of major geochemical characteristics of Mart 27.

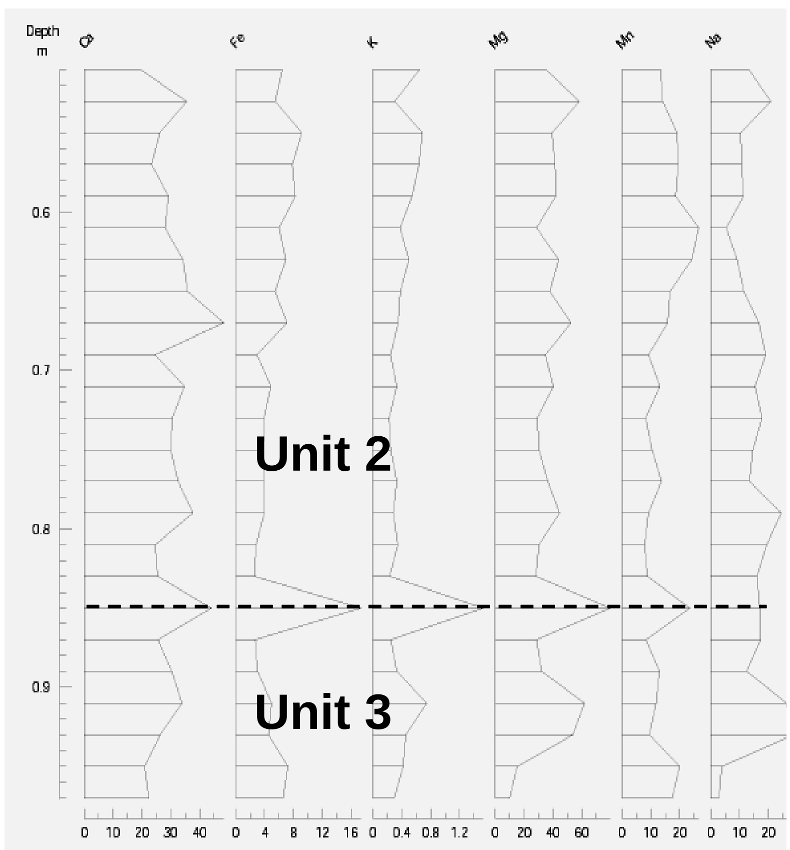

Figure 7.7- Ca, Fe, K, Mg, Mn and Na concentrations
(mg of element/g of dry weight) on core Mart 27.

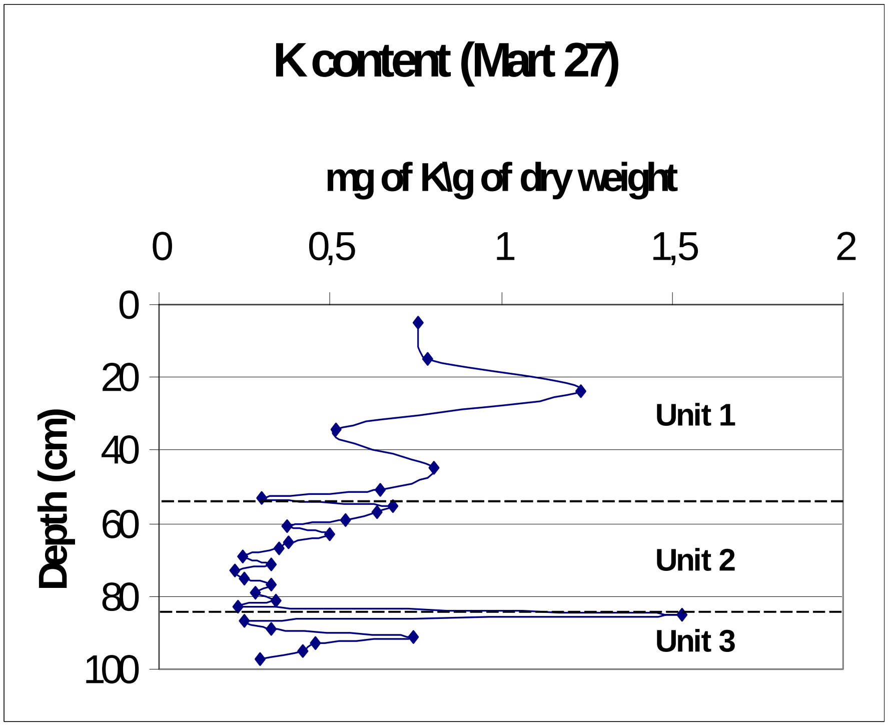

Figure 7.8- K concentration on core Mart 27.

XRF analyses were conducted at the Environmental Research Centre, Brunel University. Analysis focused on the contact between Unit 3 and Unit 2. Figures 7.9, 7.10 and 7.11 exhibited respectively the XRF results of the top of Unit 3, base of Unit 2 and middle of Unit 2. The results indicate a sharp increase of the concentrations of Si, Fe, Ca and K at the base of Unit 2. The result from middle of Unit 2 showed a considerable decrease of Si, Fe and Ca, but especially a sharp decrease of K.

The geochemical results were complex but interesting. The results will be discussed in more detail in Chapter 8. However, one can conclude that the geochemical results translate the sedimentological and stratigraphic changes. The transition between Unit 2 and Unit 3 was clearly marked with increases in carbonates, Fe, Ca, Si, K and decreases in organic matter.

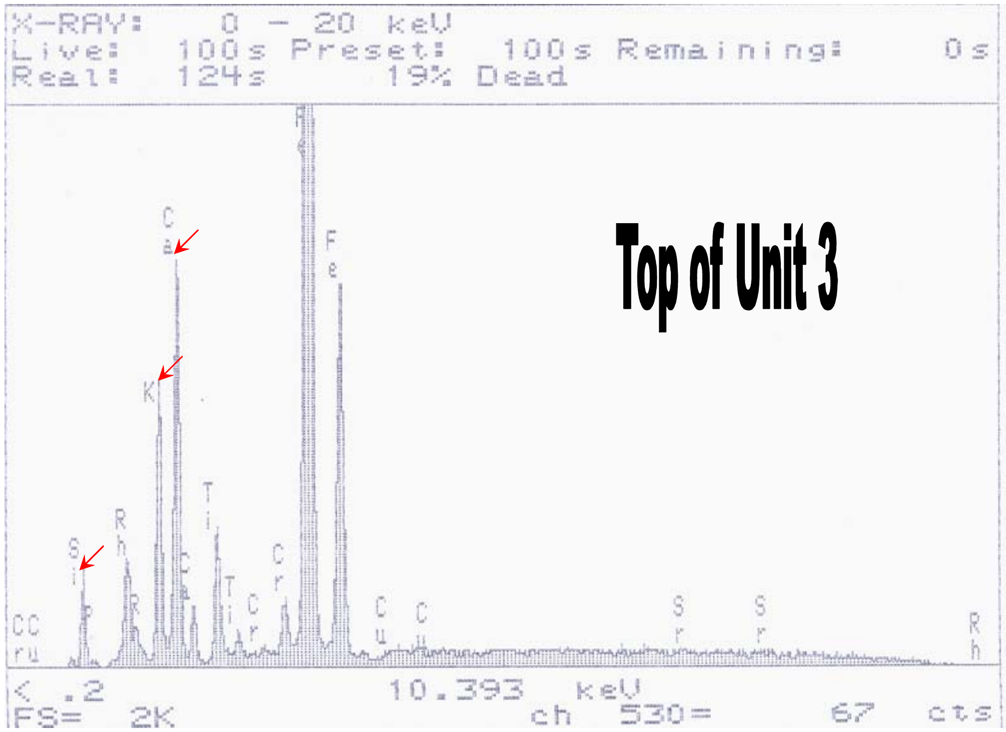

Figure 7.9- XRF analysis on core Mart 27 (top of Unit 3).

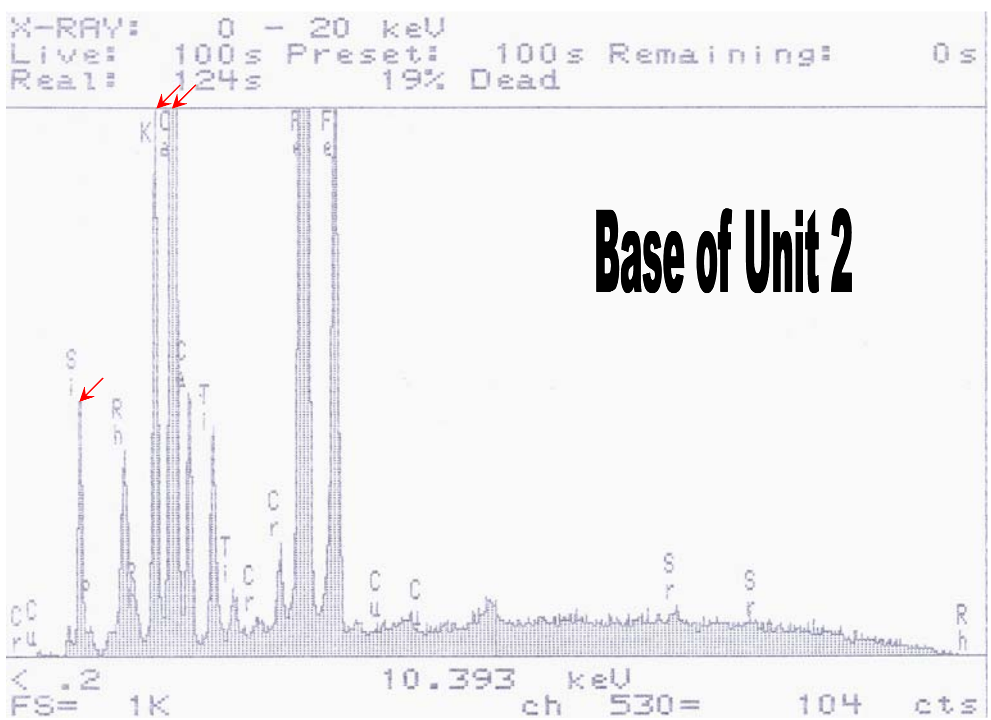

Figure 7.10- XRF analysis on core Mart 27 (bottom of Unit 2).

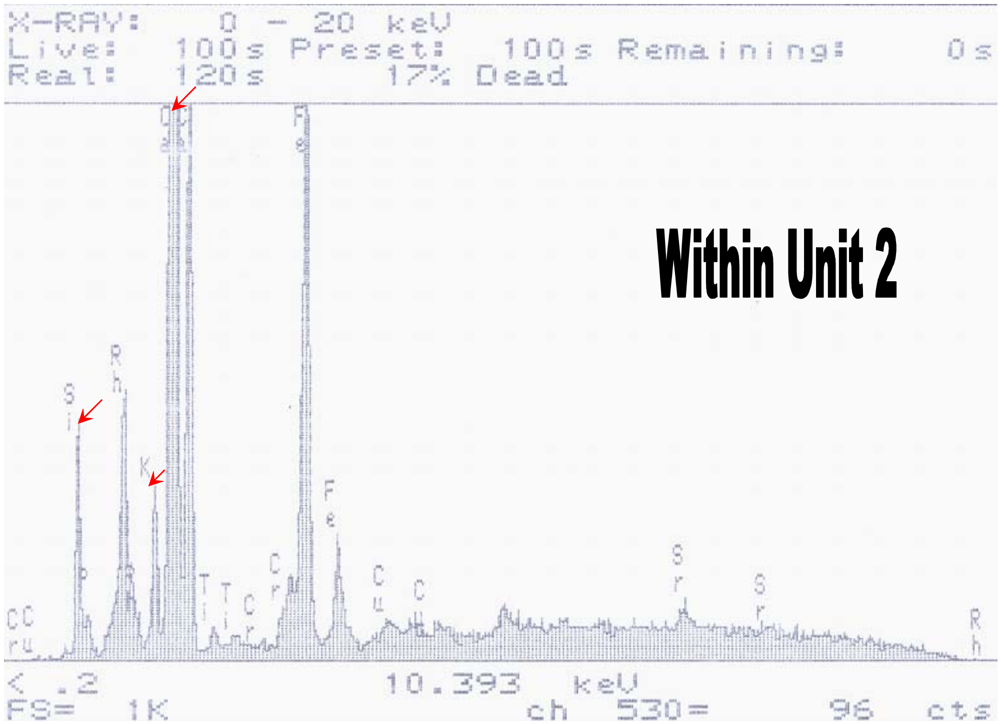

Figure 7.11- XRF analysis on core Mart 27 (within Unit 2).

7.4.7- Grain size analysis

Laser granulometry analyses were conducted at the base of Unit 2. Malvern 2000 Laser Series was used to analyse the grain size of Unit 2 of core Mart 27 and results are presented in Figure 7.12. Immediate underlying and overlying units were also analysed. Results clearly indicated that Unit 2 is coarser than the underlying and overlying units. Also noticed is the fact that Unit 2 fines upwards. A sharp increase in sand was registered at the bottom of Unit 2. Clay and silt content decreased and are almost unnoticed within Unit 2. Average grain size increased at the base of Unit 2 and presented a slight decrease towards the top of Unit 2.

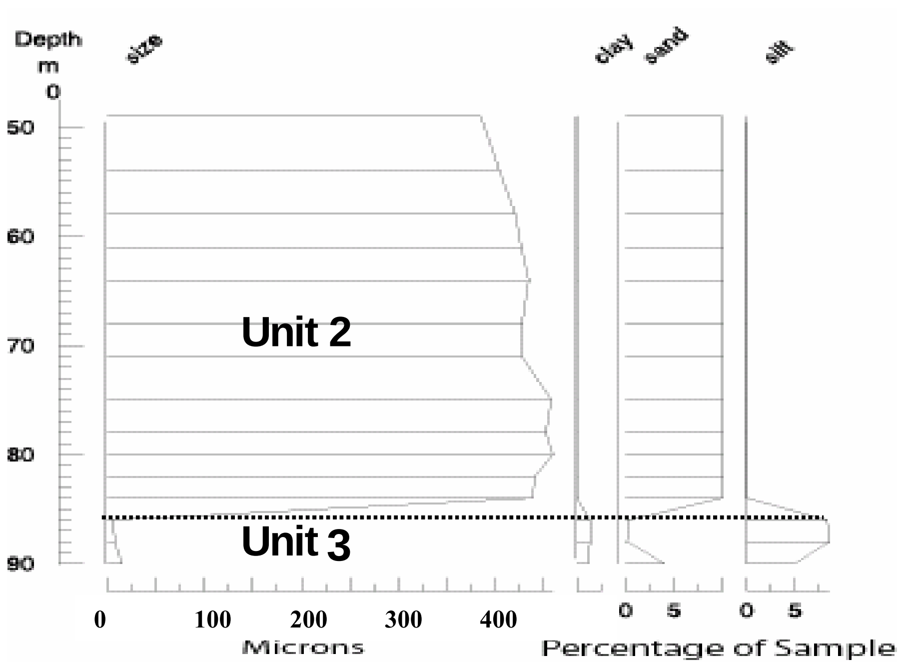

Figure 7.12- Grain size analysis of core Mart 27.

7.4.8- Palaeontology

This research did not conduct any palaeontological study. However Kortekaas (2002) analysed Foraminifera from core 9 and from core 45. Units were characterised by Kortekaas (2002). Unit 4 presented species characteristics of an estuarine or intertidal environment (e.g. *H. germanica*, *A. beccarii*, *A. beccarii* var. *batavus*, *Q. seminulum* and *Elphidium* spp.); Unit 3 did not present any foraminifera; Unit 2 exhibited a predominantly marine assemblage with the presence of *E. macellum*, *E. crispum*, *Q. seminulum*, *C. refulgens*, *C. lobatulus*, *E. repandus* and and *A. beccarii* var. *batavus* but also brackish species such as *H. germanica* and *A. beccarii* were detected; Unit 1 presents very low concentration of foraminifera and a high marsh assemblage with the presence of *H. germanica*, *Trochammina inflata* that is replaced towards the surface by *Jadamina macrescens*. One should expect similar palaeontological results on Mart 27. However, the results presented should only be used in the interpretation of Unit 2.

7.4.9- Dating results

The dates can be obtained by correlation with previous analysis presented by Kortekaas (2002). The technique used in samples from trench 1 was luminescence dating. The dating of the Martinhal samples was problematic. The units were not in chronological order (Table 7.2). Kortekaas (2002) explained that "since the lower contact of Unit 2 is erosive and intraclasts of the underlying material have been found in the sand layer, it can be assumed that the top of unit 3 was eroded by the tsunami and consequently an older date than AD 1755 is expected". It is also important to bear in mind that when the barrier was established around 1702±679 years a go, Martinhal was transformed in a brackish lagoon.

Sample	**Unit**	**Depth (cm)**	**Years (BP)**
MRT 4	1	20	1844±304
MRT 3	2	70	3199±2008
MRT 2	2	90	74±45
MRT 1	3	110	397±33
MRT 5	3	240	1702±679
MRT 6	4	285	3655±673

Table 7.2- Results of Luminescence dating for trench 1 (Kortekaas, 2002)

7.5- Conclusion

Martinhal, located in the south coast of Portugal, is a flat valley subjected to frequent abrupt marine invasions. The stratigraphy of Martinhal was studied previously. However, one core Mart 27 was the study object of this chapter. Martinhal core (Mart 27) was submitted to a wide range of techniques to establish/confirm the tsunamic origin of Unit 2. The results presented confirmed that Unit 2 presents many of the tsunamic diagnostic characteristics. Stratigraphic and granulometric proxies confirmed the abruptness and uniqueness of Unit 2.

Geochemical data indicated that Unit 2 was deposited by an abrupt marine invasion. Geochemical data revealed (within Unit 1) that other "smaller" events (storm deposits) left a geochemical signature. The organic content and carbonates content stressed the marine origin of the deposit. XRF results indicated a sharp increase of Si, indicating the sandy composition of Unit 2.

In conclusion, all the proxies and results obtained confirmed that Martinhal was subject to several abrupt marine invasions that left a sedimentological signature. The results from Martinhal are compared with the results from Lagoa de Óbidos in Chapters 8 and 9.

8. Discussion

8.1- Lagoa de Óbidos

Tsunami deposits can be recognised in stratigraphy (Chapter 3) exploring a wide range of proxies, including stratigraphic, granulometric, palaeontological and geochemical features.

The results obtained indicate that, at least, one major abrupt marine invasion was identified in lagoonal stratigraphy. Unit B (Event Unit) possesses some tsunamigenic characteristics. Unit B has a unique stratigraphic signature within the stratigraphy of Lagoa de Óbidos. The stratigraphic analyses demonstrated that Unit B fines inland and is non-existent on core OB2 (easternmost station). Moreover, a loading structure was detected at the base of Unit B on core OB1. A sequence of 3 fining upwards sub-units was detected within Unit B at OB1. Furthermore, the lower contact of Unit B is erosional in all cores. Other tsunamigenic stratigraphical features presented in Chapter 3 were not detected.

The sedimentological influx to the lagoon has two sources, marine (coarser sediments - sand) and fluvial (finer sediments-silt and clay). In granulometric terms Unit B is unique in the stratigraphy of the lagoonal sediments. This event presented an anomalous increase in the sand content and a sharp decrease in the clay and silt content. In addition, a general increase in the average grain size was also present. However, two other major events (increases in average grain size and geochemical changes) were detected at approximately 60cm and 120cm (Figures 6.13 to 6.21 and Tables 6.2 to 6.5). Moreover, these two events did not leave any lithological signature. Furthermore, each core receives a specific balanced input from marine and fluvial influxes, contributing for specific results in each station. In cores OB1 and OB4 at approximately 120 cm deep a sharp grain size increase was detected. This event also revealed an anomalous increase in the sand content and a sharp decrease in the clay and silt content. Granulometrically this event was not detected in the easternmost stations. Another event (sharp increase in average grain size) was detected at the base of Unit D but again only on cores OB1 and OB4.

Palaeontological studies conducted focused on the base of Unit B. Results demonstrated that due to the increase of plant fragments, broken shells and twig/roots, one might conclude that a strong high-energy event was responsible for the deposition of Unit B. However, Mollusc identification only detected brackish species. The Mollusc species identified can be found *in situ* within the coastal area of Lagoa de Óbidos.

Extensive and complex geochemical studies were conducted. Among other conclusions, the geochemical results proved that it is possible to correlate granulometry, stratigraphy and geochemistry. Organic matter content and carbonate content once more exhibited different patterns for OB1-OB4 and for OB2-OB5. The *loss-on-ignition* results were not obvious, however some conclusions might be assumed. First, very slight decreases in organic matter content were detected at base of Unit B in all cores, except OB2. In terms of carbonates content slight increases were detected in all cores at the base of Unit B, at the 120cm event and at the base of Unit D. Both results (e.g. organic matter and carbonates content) indicate a probable increase of marine influences at the events (e.g. more salinity leads to less organic matter; more carbonates content due to an increase in shells brought into the lagoon).

Atomic Absorption Spectroscopy results were complex. A correlation was possible with the 3 events detected in the granulometric analysis. In OB1 Unit B is marked with increases in most elements. Three sharp increases were present at the base of Unit B (exactly the same 3 peaks in granulometry). Elements such as Fe, K, Mg, Na presented this feature. At the base of Unit B sharp increases in Al, Mn and Zn were present. The increases in concentration are result of a major sedimentological influx, probably with a marine origin due to increases in K and Mg, for instance. Mn increase can be explained by anoxic conditions caused by the abruptness of the event. The 120 cm event was also present with sharp increases in Ca, Mg and Zn. The sedimentological source for the 120 cm event is probably the same as the source of Unit B.

However, the 120 cm event has a lower intensity and extension. In OB4 the 3 events are present marked with unique peaks at the respective depths. Increases were detected in elements such as Al, Fe, K, Mg and Na. OB5 revealed more complex results with frequent oscillations but with slight increases in concentration at the base of Units B and C. Interestingly OB2 also presented a geochemical signature of the 3 events. Increases were detected in Al, Ca, Fe, K, Mg and Na, again the sedimentological influx was probably marine due to the presence of "marine elements". Mn also presents peaks around 80 and 120 cm.

The geochemical results confirmed that Unit B was a unique stratigraphic event. Moreover, geochemistry also confirmed the existence of 2 other events. Correlation between granulometric and geochemical data was clearly possible.

Magnetic susceptibility results were useful correlating the different cores. However it was extremely difficult to correlate the magnetic susceptibility results with the stratigraphy. Exceptions were the base of Unit C on core OB1 and OB2 and OB5 present peaks at base of Unit B and at 120 cm deep.

X-ray and digital photography was taken and it was valuable identifying coarser grains and broken shells in OB1 (section). Probably, this is a technique that was not fully explored due to time and financial constrains.

Dates obtained for the event (OSL) and for the top of OB4 (^{210}Pb) were problematic. There are no historical records of a major abrupt marine invasion around 1850. The complexity of the sedimentological succession of events might explain the underestimation of the age. Moreover, the imprecision in OSL dating for this type of events is still a matter of discussion. Sedimentation rate was established by ^{210}Pb. However, due to the hydrodynamic and sedimentological cycles within Lagoa de Óbidos, if extrapolating the sedimentation rate, one can only speculate with the results. It is important however to have in consideration in the interpretation of the OSL results that the sedimentary environment within which this method is most sensitive is generally sub-aqueous contexts within which the longer wavelengths of sunlight dominate, and may therefore be directly applicable to the dated deposits of OB1 indicating that this sample may have been fully bleached prior to burial.

The underestimation of the age expected for the event using OSL dating had previously been detected (e.g. Boca do Rio and Martinhal). In the Boca do Rio, Barbara Mauz (2003) obtained an estimated age of 165±18 years for the event layer detected by Hindson & et al. (1999). The same event had previously been dated by Dawson et al. (1995) and an age of 194±76 years was attributed to this deposit. The Martinhal results were discussed in chapter 7. The complexity of both method and sedimentary event increases the difficulty to obtain an accurate date.

The sedimentation rates obtained with OSL and with ^{210}Pb are different, as expected. According to Freitas (1989a) the lagoon has increased the sedimentation rate during the last century. As many coastal lagoons, Lagoa de Óbidos is silting up, due to the hydrodynamic and sedimentological cycles, previously described in this chapter. It is interesting to note that the base of Unit D is marked by a decrease in the ^{210}Pb unsubstantiated values. Using constant sedimentation rate (which is not the case of Lagoa de Óbidos) the year obtained for the base of Unit B is AD1910.

Based on these results a model for the recent evolution of Lagoa de Óbidos is proposed. The Portuguese coast was affected by the AD 1755 tsunami. Lagoa de Óbidos is no exception. This lagoon only communicates with the sea through a channel, which is artificially open regularly, especially since the 50's. The AD 1755 tsunami was a major abrupt marine invasion and was responsible for the deposition of Unit B. The enormous amount of sediments transported by the tsunami forced the closure of channel of communication with the sea. This fact made possible the deposition of finer sediments (Unit C). The Aberta was then artificially reopened in the 1950s and Unit D started to be deposited. The 60 cm event might be related with the opening of the channel with the use of machines in the 50's (assuming that the sedimentation rate established by ^{210}Pb is accurate). The 120 cm event is more difficult to explain. However, all results indicate that the origin for the 3 events was the same (e.g. marine origin). In conclusion, one might assume that the 120 cm was deposited by an anomalous (and undetected in historical records) storm surge.

8.2- Martinhal

A unit deposited by the AD 1755 tsunami was previously identified in the stratigraphy of Martinhal by Kortekaas (2002). Other events are present within Unit 1, however the analyses conducted in this Unit, were restricted due to the fact that the samples were stored in sample bags. Martinhal is a flat estuarine valley frequently subjected to storm surges. A group of proxies was conducted in order to compare a known tsunami deposit and its characteristics (Mart 27) with a possible tsunamigenic Unit (Lagoa de Óbidos-Unit B).

The stratigraphy of Martinhal presents a major lithological unit (Unit 2) deposited by an abrupt marine invasion (e.g. AD 1755 Tsunami). Moreover, 3 other units were identified on core Mart 27 and the presence of small coarser sub-units was detected in Unit 1. Rip-up clasts and erosional contact was also observed at the base of Unit 2.

Magnetic susceptibility measurements were conducted on Mart 27 and Unit 2 was linked with a progressive and continuous decrease of the values. No obvious relations between the lithological units and the magnetic susceptibility values were recognised.

X-ray and digital photography permitted the recognition of rip-up clasts and of several coarser grains within Unit 2.

Geochemical results were quite significative. *Loss-on-ignition* results demonstrated that the deposition of Unit 2 was characterised by the sharp decrease of organic matter and the abrupt increase of carbonates. These changes were caused by the increase in salinity and the increase in shells fragments caused by the AD 1755 tsunami sedimentological deposition. Atomic Absorption Spectroscopy analyses of Ca, Fe, K, Mg, Mn, Na and Pb were conducted in the top meter of Mart 27. Results demonstrated the unique characteristics of Unit 2. Abrupt increases of the concentration of Ca, Fe, K, Mg and Na at the base of Unit 2 were registered. Unit 2 was limited by 2 peaks of Mn, indicating, probable, anoxic conditions caused by the abrupt deposition. Other events were detected with increases in concentration of Ca, Fe, Mg and Na at approximately 68 and 54 cm deep (within Unit 2). Other events also marked by increases of Fe, Mg and Na were also detected within Unit 1 at approximately 45 and 22 cm deep. The X-Ray-Fluorescence analyses were conducted exclusively at the base of Unit 2 and the immediate underlying and overlying layers. Results demonstrated the increase in Si, Fe, K and Ca. The increase in Si can easily be explained by the increase in quartzitic sand that constitutes the majority of Unit 2. The increases detected in elements such as Ca, Na, Fe, Mg and K can be explained by the sedimentological content that was deposited by the AD 1755 Tsunami. Two elements deserves special notice, K and Fe present by far the highest value in concentration at the base of Unit 2. The marine origin (Chapter 3) of these elements reinforces the theory that Unit 2 was deposited by an abrupt marine invasion, possibly the AD 1755 Tsunami.

Granulometric analyses were also conducted in Unit 2 and in the immediate underlying and overlying layers. Results demonstrated that Unit 2 is in strong contrast with the underlying layer. From a clay/silt dominated environment (Unit 3) the core becomes sandy dominated with Unit 2. The cause of the change is obviously and abrupt marine invasion that caused the deposition of Unit 2.

The geomorphological history established by Kortekaas (2002) can be accepted. The barrier was breached by the AD 1755 Tsunami and after that event a succession of marine invasions affected the Martinhal lithology.

The analyses conducted and the results obtained indicate that an abrupt marine invasion deposited Unit 2, possible the AD 1755 Tsunami. This Unit 2 exhibits many sedimentary characteristics of a tsunami deposit. The dates obtained by Kortekaas (2002) were not able to confirm that Unit 2 was contemporary of the AD 1755 Tsunami. However, all other proxies seem to indicate that Unit 2 was deposited by the AD 1755 Tsunami. This research confirms such hypothesis.

8.3- Evidence of tsunami deposits

Chapter 3 presents a group of diagnostic criteria to identify tsunami deposits. To recognise tsunamic units a group of stratigraphic, granulometric, palaeontological and geochemical criteria should be present in the studied unit. Both locations presented Units with some tsunamigenic characteristics (Table 8.1).

Diagnostic Criteria	**Type of criteria**	**Lagoa de Óbidos (Unit B)**	**Martinhal (Mart 27) (Unit 2)**
Sheet of deposits that generally fines inland and upwards	Stratigraphic	***Detected***	***Detected***
Each wave can form a distinct sedimentary unit	Stratigraphic	*Not Detected*	*Not Detected*
Distinct upper and lower sub-units representing run-up and backwash	Stratigraphic	*Not Detected*	*Not Detected*
Lower contact is unconformable or erosional	Stratigraphic	***Detected***	***Detected***
Can contain intraclasts of reworked material	Stratigraphic	*Not Detected*	***Detected***
Loading structures at base of deposit	Stratigraphic	***Detected***	***Detected***

Diagnostic Criteria	**Type of criteria**	**Lagoa de Óbidos (Unit B)**	**Martinhal (Mart 27) (Unit 2)**
Particle and grain size range from boulder layers (up to 750 m^3), to coarse sand to fine mud. However, most deposits are usually recognised as anomalous sand units in peat sequences	Granulometric	***Detected***	***Detected***
Generally associated with an increase in abundance of marine to brackish-water diatoms	Palaeontological	*Not detected*	*Not detected*
Marked changes in Foraminifera (and other microfossils) assemblages	Palaeontological	*Not analysed*	***Detected*** *(Kortekaas, 2002)*
Individual shells and shell-rich units are often present	Palaeontological	***Detected***	*Not detected*
Often associated with buried terrestrial plant material and/or buried soil	Palaeontological	***Detected***	*Not detected*
Shell, wood and dense debris often found "rafted" near top of sequence	Palaeontological	*Not detected*	*Not detected*
Increases in the concentration of sodium, sulphate, chlorine, calcium and magnesium occur in tsunami deposits relative to under and overlying sediments; indicates saltwater inundation	Geochemical	***Detected***	***Detected***

Table 8.1- Diagnostic criteria to recognise tsunamis (for references see Chapter 3)

In conclusion, one might conclude that a possible tsunamic event was responsible for the deposition of Unit B, in the stratigraphy of Lagoa de Óbidos, and for the deposition of Unit 2 in Martinhal. Due to the uniqueness of the Units in coastal stratigraphy, one can assume that a major tsunami could have deposited those units. The AD 1755 Tsunami was the biggest tsunami to affect the Portuguese coast and it was the probable source of Unit B at Lagoa de Óbidos and of Unit 2 at Martinhal, even if the dates obtained did not corroborated this hypothesis. The problem with the dates of the Units can be explain by both the complexity of the sedimentological and hydrodynamic cycles and by the inaccuracy of the luminescence dating for this type of events.

8.4- Comparisons between Martinhal and Lagoa de Óbidos

Lagoa de Óbidos and Martinhal are both coastal areas subject to frequent marine invasions. However, the sand barriers that separate Lagoa de Óbidos and Martinhal from the Atlantic Ocean affect the sedimentological cycle of each location. The sand barrier at Lagoa de Óbidos is a consolidate barrier that serves as a major impediment for the deposition of marine deposits within the lagoonal stratigraphy. In contrast the barrier at Martinhal is easily bypassed by frequent storm surges. This can easily explain the more frequent storm surges deposits (Unit 1) in Martinhal. Furthermore, the distance from the coastline to the stations used in Óbidos varies from 1500 metres to 3000 metres, while Mart 27 is located just over 100 metres of Martinhal beach. In Lagoa de Óbidos the high energy of normal storm surges is not able to transport sediments further inland (e.g. the limit is the overwash fan).

In conclusion, as presented in Table 8.1, Martinhal and Lagoa de Óbidos present a similar lithostratigraphic signature of an abrupt marine invasion (possibly the AD 1755 tsunami). Moreover, the specific geomorphological features (e.g. sand barrier) favoured the presence of more abrupt marine invasions deposited in the Martinhal stratigraphy when compared with the lagoonal stratigraphy at Lagoa de Óbidos.

8.5- Limitations of differentiation between tsunami and storm deposits

The differentiation of abrupt marine invasions stratigraphic signatures is crucial for an accurate hazard assessment of any coastal area. In recent years particular attention has been devoted to this area of research. However, with the exception of specific local sites and correspondently specific hydrodynamics and sedimentological cycles, the distinction between different types of abrupt marine invasions has not been possible, questions remain if it is possible at all.

This research emphasises the difficulties of the sedimentological differentiation between different abrupt marine invasions.

In the Lagoa de Óbidos samples 2 other events were detected, around approximately 60 cm and around approximately 120 cm. The marine character of the two events was proved using geochemical and granulometric analysis. Those events did not present any stratigraphic signature. However, the granulometric and geochemical features where similar to the features revealed by Unit B. The major granulometric and geochemical difference between those two events and Unit B is the uniqueness and stratigraphic signature of Unit B. The 60 cm event can be explained by the abrupt opening of the sand barrier which lead to the deposition of coarser material and created the conditions for the deposition of Unit D (coarser clay). However, the penetration inland also suggests that only a high energy event, such as a storm surge was capable of transport coarser sediments so far inland. For the 120 cm event a similar explanation can also be proposed.

In conclusion, this research was not capable of distinguishing deposits laid down by abrupt marine invasions, except the fact that Unit B has a strong stratigraphic signal and because Unit B was unique in terms of the stratigraphic column.

8.6- Comparison of results obtained with different proxies

A wide range of techniques was used to detected abrupt marine invasion deposits. Proxies such as historical record, coring, stratigraphic description, x-ray and digital photography, magnetic susceptibility, geochemical analyses, grain size analyses, palaeontological studies and dating methods were used.

The results obtained lead to some conclusions. First, the specific conditions of the studied area should condition the choice of techniques to use. The recognition of abrupt marine invasions requires a multi-proxy analyse. However, in the case of Lagoa de Óbidos and Martinhal the stratigraphic uniqueness of Units B and 2, respectively, was the decisive factor to distinguish those events from others registered in the stratigraphy of the studied areas. Moreover, the geochemical signal was detected in stations were no stratigraphic or granulometric signature was recognised. However, this was due to the specific conditions of Lagoa de Óbidos (balance between marine and fluvial sedimentological influxes) and cannot be applied indiscriminately in every location. Other proxies such as magnetic susceptibility x-ray and digital photography and palaeontological studies, although helpful were not conclusive in the determination and differentiation of the deposits. The dates obtained were problematic and this proved to be the main difficulty of this research. This is a common point with other abrupt marine invasions research. The choice of dating methods was adequate, according with the previous literature. However, for both sedimentological and methodological reasons, an underestimation of the ages was obtained. Future work may explore other dating methods.

9. Conclusion

9.1- Summary

This research and the results presented in this thesis focused on two coastal areas of Portugal, Lagoa de Óbidos and Martinhal, and the effects of abrupt marine invasions in the local stratigraphy.

Lagoa de Óbidos is a shallow lagoon located in the Western central coast of Portugal. Martinhal is flat estuarine valley located in the south coast of Portugal. Martinhal and Lagoa de Óbidos, as many coastal areas in Portugal, were affected by the AD 1755 tsunami. Geomorphological changes were caused by the tsunami. Moreover, the possibility of detecting a tsunami sedimentary signature of the AD 1755 Tsunami in Lagoa de Óbidos and the comparison with a recognised tsunamigenic unit is the overall aim of this thesis. To detect tsunamigenic deposits a wide range of techniques was used and diagnostic criteria (Chapter 3) were followed.

Another aim of this research was to compare a known tsunami deposit (Martinhal) with a possible tsunami deposit (Lagoa de Óbidos). To achieve that objective the samples were submitted to the same proxies and results were compared. Correlations were established between the two studied sites.

An additional objective was to detect units deposited by other abrupt marine invasions and compare them with the tsunamigenic Unit. In both locations other events were detected. Although the main focus of this thesis was the tsunamigenic unit, geological comparisons were possible between the tsunami and other marine invasions deposits.

A further aim was to analyse which proxy, if any, provided more accurate results to detect deposits laid down in coastal areas by abrupt marine invasions.

In conclusion, this thesis detected one Unit, probably deposited by the AD 1755 Tsunami in each location. Other events deposited after abrupt marine invasions were also detected in both sites. Comparisons were established between both tsunamic Units and between each tsunamigenic deposit and other events recognised in the same studied are. The accuracy of each proxy was analysed to conclude which proxy, if any, was more precise recognising abrupt marine invasions.

9.2- Future work

This thesis has shown that in the specific conditions of deposition of Lagoa de Óbidos and Martinhal sites the distinction between storm surges and tsunamis is not clear and provides an important lesson for tsunami research along the West coast of Portugal. Therefore it is possible, even likely, that tsunamis are underestimated in the sedimentary record in this area.

It is important that future research searches for locations with well documented episodes of both tsunamic and storm deposits. Moreover, it would be important to conduct this type of research in the most diverse locations around the World. If common characteristics were detected to differentiate abrupt marine invasions deposits, a new group of diagnostic criteria could be proposed.

The methodology followed in this research is consistent with other work on tsunamis, and therefore created a dataset that can be compared with other areas; it is clear that the methods used are appropriate and provided the best set of data that could be obtained within the constrains of this research programme. A wide range of proxies was used. Historical records were an important source of information and contributed for the choice of locations. The geomorphology of the studied area was also decisive factor to the selection of locations. A accurate geomorphological and historical research prior to any coring campaign should always be follow. The specific locations of the cores to collect should be determined by specific hydrodynamic of the region. The other proxies used (e.g. stratigraphic description, x-ray and digital photography, magnetic susceptibility, geochemical analyses, grain size analyses, palaeontological studies and dating methods) should be conducted to verify if the identification diagnostic criteria is detected in the studied area.

It is crucial that future research contributes to minimize the uncertainty factor in the recognition and differentiation of deposits laid down by abrupt marine invasions.

This thesis hopes to contribute to a better knowledge and understanding of the sedimentological characteristics that characterize abrupt marine invasions.

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